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A PARAMETRIC ANALYSIS

OF HELSTAR

THESIS

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OF HELSTAR

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Space Operations

by

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December 1983

Approved for public release; distribution unlimited

Preface

With the recognition of space as a new field of operations has come the need to determine military capabilities in this new environment. Recent emphasis in this area has made the HELSTAR model a very valuable tool for strategic analysts and planners. However, since decisions might be made that would commit large numbers of personnel and massive quantities of funds to a space-based ballistic missile defense system, the decisions made should be based on sound judgement and reliable methods.

Since HELSTAR could be used for this purpose, the user should have a high level of confidence that the program is reliable and effective. But since the nature of this type of defense system is so complicated, any results obtained by the use of HELSTAR can be considered to be "approximate" at best. However, the structure of HELSTAR is such that by using it and becoming familiar with its capabilities, the user should be able to gain a deeper understanding of the dynamics and interactions between the elements of a laser defense system.

HELSTAR is a very capable program but it does contain a limitation and an error; users should be aware of these before making any comparisons between systems or basing schemes.

This writer would like to thank Dr. Edward J. Dunne for the guidance and advice offered throughout this research effort. Special recognition is also offered to Maj James K. Feldman for comments and advice about realistic attack scenarios, Maj Joseph W. Coleman for help in using the Cyber computer system, and to Capt Joseph Wysocki for help and guidance in using the HELSTAR program.

Also, special recognition must go to an individual without whose continuing support and devotion, this project would never have been finished. The efforts of Rose Miklasevich must be recognized for what they are; total support and encouragement were offered throughout, but especially when needed most. Hopefully, this work is better (and more useful) because of her support. Finally, a note of thanks to Diane Katterheinrich for her efforts and typing skills -- an excellent job under tight time constraints.

James Miklasevich

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Abstract

The HELSTAR program is analyzed with a view towards verification and validation. The program is divided into three major areas for parametric study: battle management, laser system and battle scenario. The effects of atmospheric attenuation of laser energy, total number of attacking missiles, type of satellite orbit, and time-dependent launches on total system effectiveness are analyzed.

In the course of the study, the effect of constellation altitude was found to have a significant effect on the size of the final "optimum" constellation. Since this altitude is determined by the program during initialization and cannot be controlled by the user, it can be considered to be a limitation of the program. Also, during the investigation of time-dependent launches, an error was found that led to invalid results. The exact location of this error could not be determined.

Aside from the above mentioned limitations, the program was found to generate logical results. It was felt that potential users could use the program with a high degree of confidence that the engagements between ICBM's and space-based lasers were being modelled correctly.

I. Introduction

Background

Recently, a deep national interest has developed in the use of new technologies for defense purposes. This has been brought about by a major policy address by the President and has resulted in the formation of a new federal agency (the Directed Energy Systems Agency) to work on laser, particle beam, and microwave technologies for use in strategic military applications (Ref 4). The fiscal 1984 budget reflects this interest with increases in funding for such areas as particle beam technology and high energy laser programs (Ref [illegible]). This country is committing a large portion of its technical and developmental resources to directed energy defense systems. As with any new type of weapon system, there are technical and political risks associated with this type of program.

Many experts disagree on the capabilities of such a system (Ref 12) and to many, there does not seem to be adequate guidance as to how the program should be conducted. William H. Gregory, the editor of Aviation Week and Space Technology, commented on President Reagan's commitment to such a program:

> Much misunderstanding has ensued over directed energy weapons and Battlestar Gallactica as the essence of the Reagan proposal. Lasers and space battle stations may be the way the effort turns, but maybe not. Basically, the program initially will seek to settle on a technically viable solution for defense. Exactly what the answers will be are yet to be determined (Ref 6).

Such new concepts and applications of unproven technologies have the potential for vast improvements in military offensive and defensive

capabilities. But there are pitfalls that must be overcome: what type of system should be developed, how should it be employed, and are resources being wasted in an effort to develop new defensive capabilities when more conventional methods are adequate?

The strategic planner must consider these and other questions in recommending the development of a new system. In order to help the analyst, mathematical models can be developed to simulate the performance of these systems and thereby allow the planner to get a better understanding of system capabilities. Smernoff claims that a "moderately sized constellation of 10-20 space platforms carrying first-generation laser weapons could place a wide range of Soviet targets in global jeopardy" (Ref 11:11). However, he does not state how he arrived at this estimate, nor even what measures of effectiveness he would use to analyze the system.

Two students from the GSO-82D class (Capts Michael Hunter and Joseph Wysocki) developed a computer simulation model (Ref 7) that simulates the dynamic interactions in various ballistic missile/space based laser (SBL) engagements. By varying various input parameters (e.g., altitude of SBL's, sea-level absorption of laser radiation, launch sites and respective target locations), the strategic analyst can determine the optimum constellation of SBL's to employ for a given scenario.

But in view of the large expenditures needed to establish such a constellation, planners should know the capabilities and limitations of their simulation models. The Hunter/Wysocki model, HELSTAR, is quite different from the models developed by previous agencies in that it can simulate the complex physical phenomena associated with a ballistic

missile/SBL engagement -- range determination, atmospheric scattering, beam propagation -- and analyze the engagement in a relatively short time. It can be a valuable tool for the strategic analyst.

When Wysocki and Hunter developed HELSTAR, they were not able to perform an in-depth analysis of the model's capabilities due to time constraints. However, they were able to exercise the model in order to further their verification and validation efforts. The model is able to incorporate many characteristics of a space-based laser defense system: number of missiles, launch sites, launch times, minimum orbital altitudes, etc. -- but they weren't able to fully examine the effects of most of these parameters on final constellation size. In view of this and in order to further the development of their model, the authors suggested that:

> additional efforts are needed to verify HELSTAR performance over the entire ranges of operational parameters and should include:
>
> 1) complete characterization of HELSTAR results as a function of variation in laser and battle management parameters
>
> 2) assessment of HELSTAR results against a wide variety of attack scenarios (Ref 7:123).

Statement of Problem

Determine if there are any design or basing parameters of a space-based laser missile defense system that might have a significant effect on overall system performance through the use of the HELSTAR model.

Objectives of the Research

The overall objective of this research is to further the investigation of a model which can be useful in assessing how effective a space-

based laser system can be in the anti-ballistic role. This research is an expanded verification and validation study of the HELSTAR model; every effort will be made to keep the research at an unclassified level by using open sources.

Therefore, the specific objectives of this thesis are the following:

1. Examine model performance as a function of laser system characteristics.

2. Simulate and analyze the effectiveness of the SBL concept against a broader range of attack scenarios.

The scope, limitations, and assumptions of this study are essentially the same as those used by the original HELSTAR team (Ref 7:6):

1. This study will not consider problems associated with launching, assembling, or fueling the system.

2. Budgetary limitations are not considered.

3. Countermeasures to negate the effects of laser irradiance are not considered.

4. It is assumed that the reader has a working knowledge of the HELSTAR program.

However, whereas Hunter and Wysocki did not address technical issues relating to system or subsystem performance, this will be a factor in this study. Specifically, the inherent limitations and effects of various laser systems will be addressed to determine how this might affect overall system performance.

Literature Review

When a program such as HELSTAR is developed, a researcher must know how accurate it can simulate the real world. Some level of confidence must be established so that final conclusions might be intelligently drawn. But how accurate can HELSTAR simulate the real world? It incorporates many features that make it physically accurate (atmos-

pheric absorption, dynamic engagements, etc.), but can we authoritatively state that it is a "good" model when these types of engagements are merely theoretical? This literature review will be dedicated to techniques and procedures used for validating and verifying simulation models.

Van Horn. Van Horn states, "validation is the process of building an acceptable level of confidence that an inference about a simulated process is a correct or valid inference for the actual process" (Ref 13:247). This seems quite reasonable -- model the process rather than study the actual process as events occur. The designer or researcher must have a reasonable degree of confidence that the model will simulate the events the researcher desires to observe; else no reasonable or valid conclusions can be derived.

If HELSTAR is used to help make strategic decisions, it must produce logical, valid results. Van Horn continues:

> "learning" from a simulation requires two stages. First, understand the behavior of the simulator itself in terms of the relations that exist between inputs and results. The second, and often more difficult task, is to translate "learning" from the simulation to "learning" about the actual process. (Ref 11:247)

When the analyst understands the relationships between the elements of his model, he can appreciate the dynamic response one element might have on another. This means that every aspect of his system must be understood in detail and any subtle interactions that might occur must also be considered. How does one develop confidence in a mathematical model?

Shannon. Shannon (Ref 10:210) follows the techniques of Fishman and Kiviat:

divide the process of evaluation into three categories:

1) verification, to insure that the model behaves as the experimenter intends; 2) validation, to test the agreement between the behavior of the model and that of the real system; and 3) problem analysis, which deals with the analysis and interpretation of the data generated by the experiments.

Shannon also suggests (Ref 10:215-219) that the model be broken into easy to manage "simple" processes and ensure that they are indeed part of the overall system being investigated. Accordingly, if a process is easy to observe and measure, the confidence involved with that process can be regarded as being quite high. The second part of Shannon's analysis involves subjecting our assumptions about the model to empirical testing. And finally, the third stage involves the ability of the model to predict the behavior of a real world system. These three stages occur continuously throughout the model's development and implementation. Thus, in summary:

1. Build a set of hypotheses concerning the manner in which the model elements react with each other.

2. Attempt to verify the assumptions of the model and operating conditions via statistical testing.

3. Compare the input and output of the model to its real world counterpart.

Part three of Shannon's analysis might present some interesting challenges to this endeavor. When considering a model of a laser defense system against an attacking force of ICBM's, the researcher cannot compare his model's results to those of a real world situation. Ghelber and Haley (Ref 4) provide some insight into this subject.

Ghelber and Haley. Ghelber and Haley studied this problem and developed a system they call "towards-validation" (Ref 5:13). They define this as "the documented evidence that a computerized model can provide users verifiable insight, within the model's domain of applica-

tion, for the purpose of formulating analytical or decision-making interferences" (Ref 5:13). This process of towards-validation is comprised of four concepts (or phases):

1. Conceptual
2. Verification
3. Credibility
4. Confidence

The conceptual phase of towards-validation occurs early during the model formulation phase. Specifics such as formal problem statements, degree of accuracy desired, assumptions and limitations, and the framework for model development are determined at this point. The analyst is conceiving of the model, limiting the scope of the endeavor and building the model. And, just as important as validation, verification is another important aspect that must be examined.

The verification phase is very similar to classical verification procedures; four basic steps are suggested:

1. Structured walk-through of the model.
2. Verification of the physical processes.
3. Simulation of predictable states.
4. Testing of stochastic events.

The structured walk-through can be quite useful; not only does it require the modeler to examine the model in detail, the designer must manually verify that events occur as expected or predicted. If necessary, calculations should be performed manually at each decision step to verify that accurate information is flowing through the system. In examining a model, the aunlyst is verifying that the processes are interacting as

intended -- or as Shannon (Ref 10:210) states, "to insure that the model behaves as the experimenter intends." In doing so, the experimenter can verify that physical processes are being simulated, and predictable states are occurring as intended. Testing of stochastic events can be accomplished by using the chi-square goodness of fit method or by the Kolmogorov-Smirnov test.

Credibility deals with the intuitive and statistical aspects of the model by using face validation and sensitivity analysis. Similar to the Turing test (Ref 10:228), face validity involves having someone (an "expert") who is familiar with this type of problem observe the model's input and corresponding output, and then giving an opinion on how well the model simulates the desired situation or process.

Sensitivity involves "tweaking" various input parameters by predetermined amounts and observing how the output of the system changes. If a system is known to be very sensitive to small changes in an input variable, then the expected output should have large changes associated with those small changes to the input variable. In essence, the analyst must determine which variables are to be controlled, those parameters whose variability most significantly affects the model.

Confidence in the model is built as the analyst uses the model and compares the output to that which would be expected. Essentially a subjective analyses at times, the level of confidence in a model is felt as an intuitive appeal by the user for the model. Statistically, it can be measured with results from real world events such as exercises, actual experiments, and independent observations of related events. For many models, though, these events have not taken place and therefore no com-

parisons can be made. The researcher is thus relegated to examining the output of the model and determining if the model is responding as expected. At this point, the expertise the researcher gained through the walk-through exercise would be extremely valuable.

Methodology

Hunter and Wysocki state in their thesis (Ref 7:123):

> An additional required assumption is that all missiles are launched simultaneously. However, this is not felt to degrade the accuracy of the model. Certainly, missiles which are "staggered" out of the cell, i.e., launched at different times, will have different relative geometries with a given SBL, and hence different kill rates. However, launching missiles later in the battle increases total exposure time of SBLs to the attack force, and hence would certainly result in improved constellation performance. To assume simultaneous launch is a conservative assumption which places a greater burden on the system.

Various "realistic" launch distributions and scenarios can be conceived and statistically tested against some baseline scenario. In this baseline scenario, the performance of five types of space-based laser systems can be examined. They are (Ref 8):

1. Solid State Lasers
2. Electrically Excited Lasers (EDL's)
3. Combustion Driven Gas Lasers (GDL's)
4. Chemical Lasers
5. Free-electron Lasers

Also, the baseline scenario will establish the performance of three types of SBL basing modes:

1. Critically Inclined Orbits, Worldwide Coverage
2. Critically Inclined Orbits, Northern Hemisphere Coverage
3. Circular, Polar Orbits

Specific arrival distributions cannot be addressed at this time since an infinite number of such engagements can be developed -- obviously, time limitations preclude such an analysis. However, several time-dependent scenarios will be developed to determine if time-sequenced launches might have an effect on overall constellation size and effectiveness.

Summary

HELSTAR has been developed to analyze the effectiveness of a space-based laser missile defense system. By varying system parameters, the analyst can determine system sensitivity to these factors and assess overall system effectiveness. To fully assess the characteristics of HELSTAR, a baseline scenario will be developed using three distinct basing modes with five types of laser systems, comparing and contrasting the effects of changes in system parameters to the baseline scenario, and determining if time-dependent launches have any effect on approximate constellation size.

Again, the reader is reminded that this is a further effort to verify and validate the model. All system parameters and subsequent results are, at best, approximations of actual system performance. If such a system were to be built and deployed, HELSTAR would be a valuable tool used to gain further insight into such a system.

The following report will describe some of the parameters which were studied and their effects on the overall efficiency of a space-based laser system. The results of these investigations will be presented along with pertinent analyses. Lastly, any limitations of the program (if any) will be discussed along with suggestions for further model refinement.

II. The Analysis of HELSTAR

HELSTAR is a computer model designed to simulate the dynamic interactions between a constellation of space-based lasers and in-coming intercontinental ballistic missiles. This model could be a valuable tool for the strategic analyst since it allows one to vary laser, missile, and target parameters and determine an approximate optimum constellation of lasers needed to destroy a given number of missiles. For example, some of the "battle management" variables are:

- total missiles in the attack
- military warning/attack assessment/command, control, communications ($MW/AA/C^3$) capabilities
- orbit selection (elliptical, circular)
- minimum engagement altitude
- types of attacking ICBM's with different material properties
- missile launch/target locations
- time of missile launch

And, some of the laser system variables are:

- laser capabilities (expressed as a beam intensity measured at a reference distance)
- atmospheric attenuation (dependent on laser wavelength, and hence, type of laser)
- total laser firing time

Conceivably, some of these parameters should have a dramatic effect on the optimal constellation, e.g., a large number of missiles in the attack force should have a dramatic effect on the constellation as com-

pared to a smaller number in the attack force. Perhaps some of the other variables might also have a profound effect on system performance. If so, how much impact would they have? In general, there will be many tradeoffs to consider in designing a system to optimize performance.

This research will examine the HELSTAR model and determine if there are any "critical" parameters in the model that must be carefully examined by other analysts. This analysis will help to further verify and validate the model. As discussed earlier, a simulation model can be quite valuable to the decision maker if there is confidence in its ability to predict future events or states. But, does HELSTAR give the analyst that confidence? Does it give accurate results? Do the results act in accordance with analytical expectations? Hopefully, the results of this study will indicate that HELSTAR is a good and accurate model.

Development of the Baseline Scenario

In order to make valid comparisons between two or more different situations, a standardized baseline scenario had to be developed. Hunter and Wysocki developed a scenario for the analyses they performed (Ref 7: 114-115) but this was found to be inadequate for this study.

In order to develop a scenario for the purpose of valid analytical comparison or testing, a certain degree of "realism" was required. To make this scenario as realistic as possible, 20 actual Soviet ICBM launch sites as depicted in openly available references (Ref 2: 14) were chosen along with five possible launch sites in international waters for sea-launched missiles.

For the initial baseline scenario, 675 missiles were assigned to the attacking force with a "successful" defense defined as one that destroyed

642, or 95%, of the attacking missiles. However, after running the scenario a number of times, it was found that this scenario used excessive amounts of computer time and abnormal delays occurred waiting for the runs to be accepted by the computer. The attacking force was subsequently decreased to a force of 500 missiles, launched from 15 different sites, with a 475 missile-kill "success" criteria. Table 2-1 and Figure 2-1 depicts the final baseline scenario. Each land-based ICBM site will launch a cell of 40 missiles against assigned targets, and every submarine will launch a cell of 20 missiles against their assigned targets.

As mentioned, some sort of baseline scenario had to be developed which would realistically exercise the capabilities of the HELSTAR model. Accordingly, it was felt that the missiles attacking their targets should be spread across the breadth of the Soviet Union to preclude any unwanted effects of geographical centrality (i.e., missile concentration) on the final constellation design. Notably, actual launch sites in the Soviet Union are somewhat uniformly spread throughout the country (Ref 2: 14). It should be strongly noted that these launch sites and "assigned" target areas were matched in a purely random fashion and reflects no knowledge on the part of this writer of any (if at all) actual targetting. It should also be noted that the spread of potential targets in the continental United States is also uniformly distributed and should preclude any unwanted effects of target density on the final outcome of the HELSTAR model. Again, it should be stressed that this scenario is based on possible launch sites and possible targets -- any particular scenario from an infinite list of scenarios could have been chosen for analysis, but this particular scenario is merely a realistic "guess".

TABLE 2-1

Launch Sites, Assignments, Cell Size

Launch Site	Target	Missiles in Cell
Derazhnya (1)	Loring AFB	40
Yedrovo (4)	Griffis AFB	40
Teykovo (5)	Grissom AFB	40
Kostroma (6)	Little Rock AFB	40
Yoshkar Ola (8)	Whiteman AFB	40
Dombarovskiiy (11)	Ellsworth AFB	40
Imeni Gastello (12)	Malmstrom AFB	40
Zhangiz Tobe (14)	McConnell AFB	40
Gladkaya (17)	Wurtsmith AFB	40
Svobodnyy (20)	Dyess AFB	40
Pacific Ocean (21)	Castle AFB	20
Pacific Ocean (22)	Beale AFB	20
Atlantic Ocean (23)	Washington, D.C.	20
Atlantic Ocean (24)	Pease AFB	20
Gulf of Mexico (25)	Barksdale AFB	20

Selection of Battle Management Parameters

Standardized battle management parameters also had to be chosen such that realistic results could be obtained and analyzed. The possible battle management parameters are:

1. Size of Battle Step Time
2. Total Missile Cells
3. Missile Trajectory Tables
4. Missile Cell Identification Tags
5. Number of Attacking Missiles
6. Battle Success Criteria

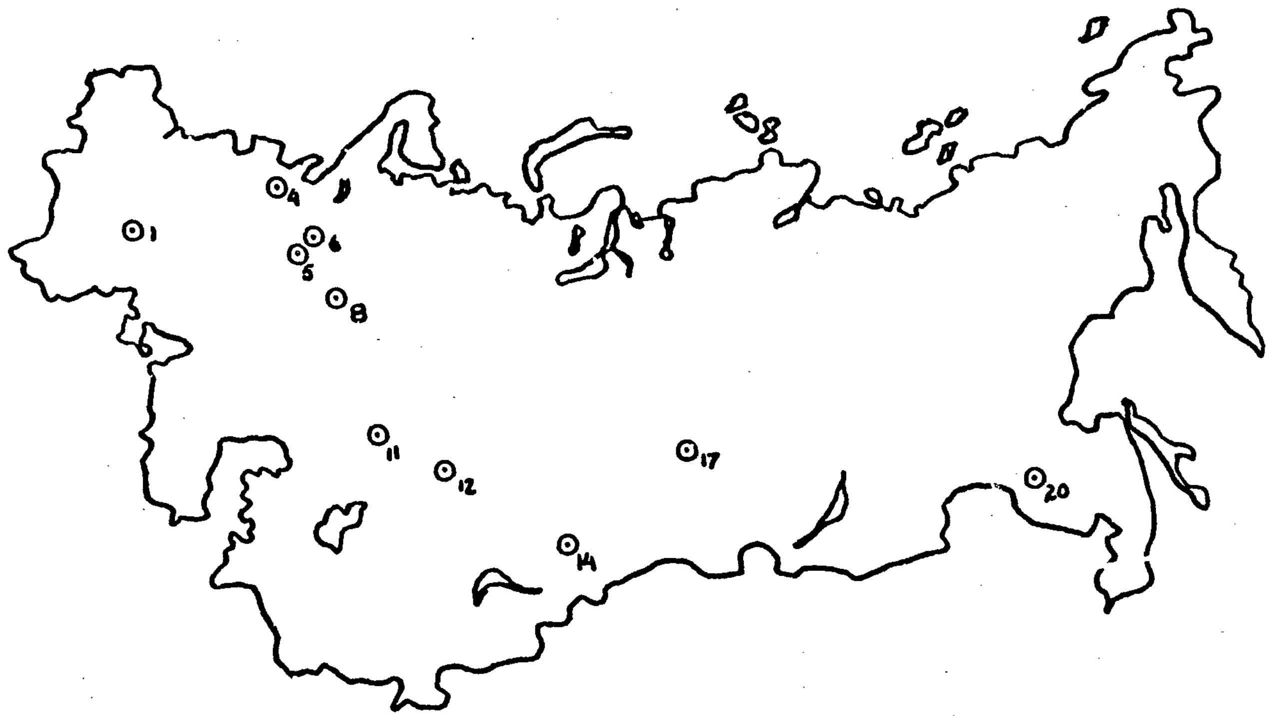

Figure 2-1. Baseline Scenario Launch Sites (USSR).

7. Attack Identification Time Lag

8. Retarget Time

9. Type of SBL Orbit

10. Minimum Targetable Altitude

In explanation of the most significant of these is given below, along with their assigned values.

Battle Step Time. This is the value of the time increment used in the simulation. For the baseline scenario, and all subsequent analyses, a value of 10 seconds was used. Hunter and Wysocki examined this parameter and it was not felt that this should be altered since smaller increments would lead to excessive use of computer time with no better results. Also, longer increments could possibly lead to invalid results. For example, time increments on the order of one second would increase computation requirements tenfold and increments on the order of two minutes (~100 seconds) could result in targeted ICBM's leaving the "engagement arena" without receiving proper service from the defending lasers (Ref 7: 19-20).

Total Missile Cells. Built into the model is a limitation of a total of 25 missile cells or sites each having their own distinct launch times. However, any number of missiles can be assigned to these cells with their respective missile characteristics, i.e., hardness against laser radiation and type of missile. In essence, a large missile force could be modelled but the analyst should be aware that large blocks of computer time would also be required. For this reason, the baseline scenario was reduced from a force of 675 missiles in 25 different launch locations to a force of 500 missiles located in 15 launch sites (Figure 2-1).

Missile Trajectory Tables. These tables represent the different flight characteristics of various types of boosters by depicting altitude and range from the launch site as a function of time through burnout. In the baseline scenario, two types of boost trajectory tables were used from the original thesis (Ref 7: 159) to represent ICBM's and SLBM's. The model has the capability to utilize three different tables (and hence, three different types of missiles), but for simplification, only two were used throughout this study.

Number of Attacking Missiles. Throughout the study, 500 missiles were used in the baseline scenario so that the simulations could be finished in a reasonable amount of time.

Battle Success Criteria. This parameter allows the user to specify how many kills the optimum constellation must make. Throughout the study, a 95% kill rate was specified, although a 100% success criteria was specified several times for comparison purposes.

Attack Identification Time Lag. This is "the type of time lag from first missile launch to SBL system activation" (Ref 7: 12), and it can be considered to be the MW/AA/C^3 delay. It can be selected from normal or uniform distributions (with user-defined parameters) or as a predetermined constant. For this research, any particular selection for this time lag could be considered to be arbitrary at best. In order to simulate an instantaneous and automatic warning and activation system, a normal distribution was selected with a mean of 0.5 seconds and a standard deviation of 0.2 seconds. Additional verification and validation efforts compared this system to one using a uniformly distributed MW/AA/C^3 time lag with limits of 60 to 90 seconds. These types of MW/AA/C^3 systems were selected

quite arbitrarily and do not represent any actual or proposed warning or attack assessment system.

Retarget Time. This represents the time needed to retarget different missiles within a given cell. These times can be selected from normal or uniform distributions, or a predetermined constant value can be assigned. For this study, a constant value of 1.5 seconds was used -- again, this does not represent any known or projected laser system.

Type of SBL Orbit. The laser system constellation can be designed based on one of two types of critically inclined elliptical orbits or circular, polar orbits. The two elliptical constellations differ in that one will provide continuous, world-wide coverage as opposed to the second design which provides for continuous coverage in the northern hemisphere with possible, non-continuous coverage in the southern hemisphere. Circular, polar orbits would also provide continuous, world-wide coverage. The three types of orbits were used throughout the study for comparison purposes, although circular orbits were used more often since they used less computer time to run to completion.

Minimum Targetable Altitude. This is the minimum altitude the SBL constellation will engage target ICBM's; this can be predetermined to compensate for weather or other factors. The baseline scenario uses 7.0 km, and the effects of this control variable on overall system performance is subsequently studied.

Laser Data

Two laser system parameters were examined to determine what effect they might have on overall system performance. They were:

1. Coefficient of Atmospheric Attenuation (α)

2. Minimum Orbit Altitude

Some parameters were not varied since it was felt that they helped to define the baseline scenario and thus should not be changed. These parameters are discussed below.

Reference Laser Intensity. This is the reference intensity at a specified distance; a value of 60000.0 watts/cm^2 was used throughout the study.

Laser Reference Range. This is the defined distance at which the laser reference intensity is measured or defined (these two parameters define system performance and can account for power generated, jitter, etc.). Throughout the study, a value of 400.0 km was used.

Reference Beam Spread. If the beam intensity cross section is assumed to be Gaussian, this parameter is the distance measured from the centerline of the laser beam to where the laser beam intensity has dropped by one standard deviation. This value was taken to be 10.0 cm, the same value used by Hunter and Wysocki.

Top of the Atmosphere. Since there is no true value or definition of the limits of the atmosphere, a value is assigned which will determine if numerical integration is required for atmospheric transmission. Consequently, the top of the atmosphere is defined to be 50.0 km.

Lethal Design Vulnerable Spot Size. In order to initialize the algorithm, HELSTAR uses the "lethal design vulnerable spot size" and the "minimum lethal edge intensity" (I_{MIN}) to calculate the maximum effective range of the laser and its limits of coverage. The lethal design vulnerable spot size is the radius of a spot on the target where I_{MIN} is measured, a value of 100.0 cm was used throughout this study.

Maximum SBL Firing Time. Since futuristic laser systems will undoubtedly have limited fuel capacities, the analyst can use HELSTAR to determine how long a given laser station must operate. For this study, the lasers can operate for 300.0 seconds.

Possible Scenarios

Hunter and Wysocki felt that for their initial analysis, simultaneous launches from all launch sites led to the most conservative constellation (Ref 7: 123), one that would possibly prove to be "over built" in other scenarios without simultaneous launches. However, time did not allow them to pursue this avenue of investigation. Accordingly, one of the main objectives of this research effort was to develop various time-dependent scenarios and determine if the model provided these expected results.

This could be accomplished in a fairly straightforward manner. Each missile cell used in the simulation has an assigned launch time; if these cells are "staggered" one can make a comparison with the baseline scenario (wherein all cells are launched simultaneously) and hopefully draw a valid conclusion about system performance and efficiency. Of course, this means that a cell of 75 missiles is launched simultaneously but due to computer resource limitations, this was the only way to approach the solution. On a grand scale (given unlimited computer resources), a large strike force can be accurately modelled by assigning to each missile cell one missile with it's assigned launch time.

However, it is possible to vary launch scenarios and make valid comparisons with the baseline scenario if everything else remains constant (battle management, constellation choice and laser weapon parameters). Conversely, various launch scenarios could be examined to determine if

the SBL system could be stressed to its limits or possibly overcome.

So, in sum, the purpose of this study is to determine how sensitive HELSTAR would be to various "critical" parameters in an effort to verify and validate the model.

Expected Results

Type of Constellation. This was the first parameter to be investigated in the course of determining the baseline scenario. There are three types of orbits that could be specified: critically inclined elliptical with world-wide coverage, critically inclined elliptical with northern hemisphere coverage, and circular polar orbits with world-wide coverage. Intuitively, one would expect the circular polar orbits to offer greater efficiency (fewer laser stations to accomplish the assigned kill rate), with possibly no difference between the two elliptical orbits. The basis for this hypothesis is that the geometry of a laser in an elliptical orbit is considerably more complex than that of a laser in a circular orbit -- orbital altitude would be constantly changing in the former case and nearly uniform and constant in the latter.

Sea-level Coefficient of Attenuation (α). Since this is a measure of how the laser radiation is absorbed and attenuated by atmospheric molecules and fine particulates, low values of α would indicate greater transmissivity and hence, more radiation on the target vehicle. There are several possible types of lasers that could be used for space basing and each have their own characteristic wavelength; therefore there could possibly be some effect on the overall SBL constellation, since the coefficient of attenuation is dependent on laser radiation wavelength (Ref 8). If atmospheric attenuation is greater for one particular laser

system than another, then there should be a greater number of satellites in the resulting constellation. This particular aspect of HELSTAR could prove to be quite valuable to the strategic analyst/planner.

Minimum Engagement Altitude. This parameter was investigated since it determines how much time is left on the "engagement clock". HELSTAR can determine how long a missile is in the burn/boost phase (via the respective boost tables), and thus can determine how long it is eligible for SBL engagement. Since missiles cannot be engaged after burnout occurs, those that are not destroyed before burnout are allowed to proceed on course to their final destination. It is this leakage that determines if a given constellation is successful or not.

The important point here is that by delaying the engagements until a higher altitude is reached, denser levels of the atmosphere would be avoided and this could prove important if a laser is utilized that has a comparatively high coefficient of attenuation. However, by delaying the engagement until higher altitudes are achieved, time requirements might dictate a larger total number of SBL's to counter the attacking force. Again, this is an aspect of HELSTAR that an analyst should find to be useful.

Missile Launch Sequences. This is an area that is open to an endless number of valid possibilities. Therefore, a "realistic" scenario is defined as one that represents a situation wherein the missiles are released according to some type of rational timetable or strategy.

If these launches are spread over a large enough period of time, more SBL's would have the opportunity to engage them. Conversely, if the launches are compressed in time, fewer SBL's would have an opportunity to

engage them and possibly the SBL's would become overwhelmed and allow a high degree of leakage. Therefore, one would expect the resultant SBL constellation to be smaller if the launches are sequenced over large time periods as opposed to quick, compressed launches.

Summary

We have examined some of the parameters which help to define the SBL capabilities. Some of these help to define system deployment (i.e., constellation orbit) but most could have an effect on system performance and efficiency. In an effort to further the overall verification and validation efforts, parametric analysis will be performed on these parameters.

One of the characteristics of a "good" simulation model is its ability to accurately predict resultant states given a predetermined change in a control variable. Therefore, if HELSTAR can respond as predicted to changes in certain parameters, then the confidence of the user should be increased. However, if counter-intuitive results are obtained, or worse, it does not function correctly, detailed analysis of the structure of the model will be required.

This chapter has presented arguments for the selection of certain parameters and how changes to those variables should affect the overall performance of the model. The next chapter will present the results of these tests and comparisons.

III. The Comparison and Demonstration of Parametric Sensitivity

This section will discuss the baseline scenarios examined in this study of HELSTAR. Basically, one of three types of orbital configurations (critically-inclined world-wide coverage, critically-inclined Northern Hemisphere coverage, and circular-polar), one of five different types of lasers, the attacking force, and kill requirements define a scenario. These five types of lasers (solid state, chemical, electric discharge, CO_2, and free electron) each have their characteristic radiation wavelength, and accordingly, their own characteristic coefficient of atmospheric adsorption (Ref 8).

These lasers operate at the following wavelengths and corresponding atmospheric transmission, T (Ref 8):

Solid State	$\lambda = 1.06\mu$, $T \doteq .70$
Chemical	$\lambda = 2.5\text{-}3.0\mu$, $T \doteq .30$
Electric Discharge	$\lambda = 5.0\mu$, $T \doteq .10$
CO_2	$\lambda = 10.6\mu$, $T \doteq .65$
Free Electron	Tuneable, $0 \leq T \leq .90$

Since the free-electron is a hypothetically tuneable laser with wavelengths in the range

$$0.1\mu \leq \lambda \leq 10\mu m,$$

a wavelength of $\lambda = 3.8\mu$ was chosen to give an optimum atmospheric transmission of $T \doteq .90$ (Ref 8:155).

The coefficient of atmospheric absorption (α) can be determined quite simply by the relation

$$\alpha = \frac{-\ln T}{L} \qquad (3\text{-}1)$$

where

T = atmospheric transmission

L = 1.82 km

At this point, a brief discussion of atmospheric transmission of laser radiation would probably be in order.

Attenuation of laser radiation in the atmosphere is given by Beer's law

$$T = \frac{I(L)}{I_o} = e^{-\alpha L} \qquad (3\text{-}2)$$

If we take the natural log of both sides of 3-2 we can easily derive equation 3-1. For our analysis α is considered to be the attenuation coefficient and is composed of two processes -- absorption and scattering. These two processes are independent of each other and are quite dependent on the frequency (or wavelength) of the laser radiation.

In the absence of precipitation there are many fine particles suspended in the atmosphere called aerosols. These common aerosols are composed of dust, water vapor, ice and their composition and density are dependent on local conditions. These suspended particles determine the amount of scattering that will affect the laser radiation.

The absorption of the laser radiation will depend on the amount of water, carbon dioxide and ozone molecules in the atmosphere. The molecules attenuate the radiation because they selectively absorb radiation by changing vibrational and rotational energy states. The two processes, scattering and absorption, are additive and their overall effect can be defined by their transmittance, T, over a given distance, L. Over a distance of 1.82 km, the transmittance as a function of wavelength is given by Figure 3-1.

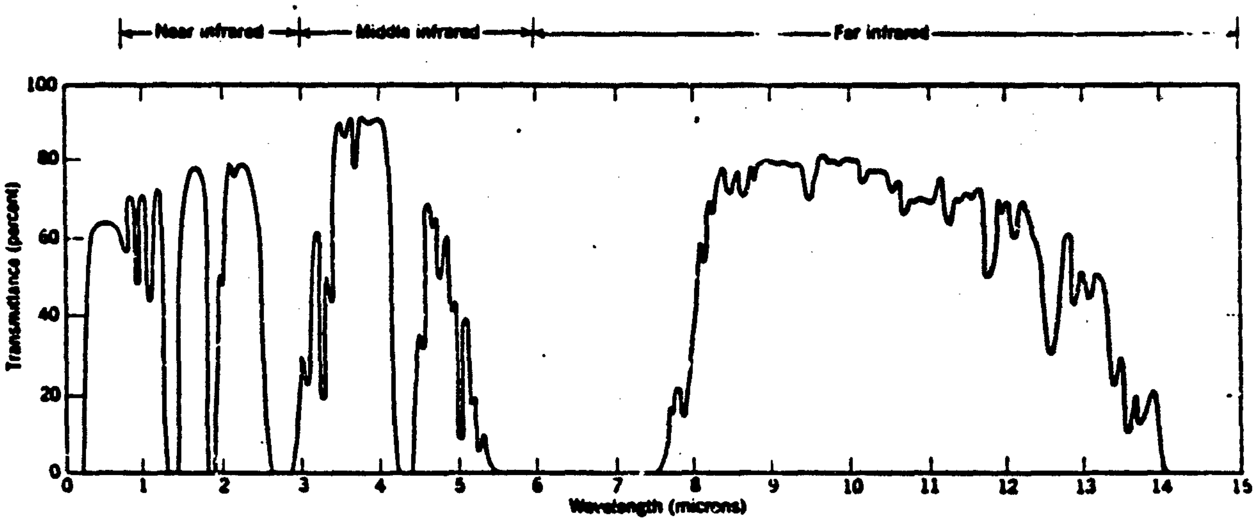

Figure 3-1. Transmittance as a Function of Wavelength (λ).

This figure is self-explanatory and it graphically portrays the effect of wavelength on radiation transmittance. We do noce that there are areas where there is no effective transmission and areas ("windows") where the radiation can be transmitted with little attenuation. Ideally, if wavelength could be selected, the region between 3.4 and 4.0 microns would offer the greatest transmission and lowest attenuation effects. However, due to the effect of scattering (which is dependent on local conditions), atmospheric attenuation must be experimentally determined. Using Figure 3-1 and equation 3-1, Table 3-1 was obtained.

Baseline Scenarios

As discussed in the previous chapter, a baseline scenario had to be developed in order to compare and contrast the effects of system parameters. The original baseline scenario consisted of an attacking force of 675 missiles with a 95% kill success criteria specified. The results of this scenario are depicted in Table 3-2. For certain wavelengths (2.5 and 5.0 microns) the final optimum constellation could not be determined due to computer resource limitations. In these cases, computer time requests of 10,000 seconds could not produce approximate optimum constellations. In a few cases even initial constellations could not be established. As a result of these limitations and in view of the fact that numerous computer simulations would be required in this study, the decision was made to reduce the number of attacking missiles, their launch sites and respective targets.

The second baseline scenario simulated 475 missile kills out of a 500 missile attack force -- Table 3-3 was the result. The similarities and differences of these two scenarios should be noted (they will be

TABLE 3-1

Wavelength, Transmission, Atmospheric Absorption

Laser	$\lambda(\mu)$	T	$\alpha\ (km^{-1})$
Solid State	1.06	.70	.196
Chemical	2.5	.30	.662
Electric Discharge	5.0	.10	1.265
CO_2	10.6	.65	.237
Free Electron	3.8	.90	.058

TABLE 3-2

Rings of Lasers/Lasers Per Orbital Ring

(Total Lasers)

As a Function of Laser Wavelength (λ)

Laser Type	λ(μm) (α)	Elliptical (Worldwide)	Elliptical (N. Hemisphere)	Circular (Polar)
Solid State	1.06 (.196 km^{-1})	11/16 * (176)	11/13 * (143)	6/9 (54)
Chemical	2.5 (.662 km^{-1})	24/35 * (840)	---	15/20 * (300)
Free Electron	3.8 (.058 km^{-1})	7/16 (112)	7/10 (70)	3/6 (18)
Electric Discharge	5.0 (1.265 km^{-1})	---	---	---
CO_2	10.6 (.237 km^{-1})	12/16 * (192)	12/14 * (168)	8/11 (88)

(* Program Limit Exceeded on Initialization)

Note: Baseline scenario with a 675 missile attack force, 95% kill success criteria.

TABLE 3-3

Rings of Lasers/Lasers Per Orbital Ring

(Total Lasers)

As a Function of Laser Wavelength (λ)

Laser Type	λ(μ) (α)	Elliptical (Worldwide)	Elliptical (N. Hemisphere)	Circular (Polar)
Solid State	1.06 (.196 km^{-1})	11/16 * (176)	11/13 * (143)	3/6 (18)
Chemical	2.5 (.662 km^{-1})	24/35 * (840)	---	15/20 * (300)
Free Electron	3.8 (.058 km^{-1})	6/5 (30)	6/4 (24)	3/6 (18)
Electric Discharge	5.0 (1.265 km^{-1})	---	---	15/20 * (300)
CO_2	10.6 (.237 km^{-1})	12/16 * (192)	12/14 * (168)	4/5 (20)

(* Program Limit Exceeded on Initialization)

Note: Baseline scenario with a 500 missile attack force, 95% kill success criteria.

discussed in detail in the next chapter); in particular, the difference in constellation size between circular and elliptical orbits is quite noticeable. In every comparable case, circular orbits yielded smaller constellations (and correspondingly smaller computer resources) as opposed to both types of elliptical orbits.

Also, smaller values of atmospheric attenuation usually yielded smaller, more manageable results. For these reasons, circular constellations composed of lasers with a characteristic wavelength of 3.8 microns ($\alpha = .058\ km^{-1}$) were used for many of the comparison studies.

It is important to stress the fact that HELSTAR is merely a model that offers an approximate description of reality, a "best guess". As such, these results are not taken to be totally accurate but merely indicative of what could be expected given the initial input variables. For any given number of system parameters, sensitivity analysis should be performed over a range of all controllable factors, i.e., minimum engagement altitude, minimum intensity on target, etc. It is also assumed that all five different types of space-based lasers are able to deliver the same amount of laser intensity at a given distance (60,000 w/cm^2 at 400 km). This would include the effects of focusing, tracking, jitter, physical parameters (output optics), etc.

Again, for certain cases in the second baseline scenario, certain laser/orbit combinations did not yield usable results, e.g., 5.0 micron/elliptical, 2.5 micron/elliptical. However, since the circular deployment yielded consistently smaller constellations, regardless of laser type, it was felt that the circular orbit should be assumed in the investigation of other system parameters.

The Investigation of the Effects of the Coefficient of Atmospheric Attenuation (α)

Since the amount of laser energy deposited on a target surface within the atmosphere is critically dependent on atmospheric attenuation, the examination of the effects of this coefficient was warranted. As can be seen from Tables 3-2 and 3-3, various wavelengths (and hence, various values of α) seem to indicate that the final constellation tends to be dependent on the specific value of α used in the simulation. This investigation of atmospheric attenuation on the final number of SBL's only considers circular polar orbits. Table 3-4 displays the result of this investigation. Notice that final approximate values of the SBL constellation are given for values of α up to and including $\alpha = .40\ km^{-1}$. Beyond values of $\alpha = .40\ km^{-1}$ the program terminated immediately after initialization due to automatic stop conditions within the program. The program will not proceed beyond initialization if the number of orbital rings is greater than 10 or the number of SBL's per ring is greater than 20.

Referring to Table 3-4, the apparent anomalies between $\alpha = .01\ km^{-1}$ and $\alpha = .02\ km^{-1}$ and $\alpha = .04\ km^{-1}$ and $\alpha = .05\ km^{-1}$ (i.e., a slightly worse coefficient of attenuation yields a smaller constellation) were examined and will be discussed later. However, in all other cases, it can be seen that as the coefficient of attenuation increases, the number of lasers in a circular orbit also increases.

This seems logical and true to intuition; as the attenuation of laser intensity increases, the number of lasers required to counter a given threat should also increase (tending to further validate the model). And, if free-electron lasers are ever developed to the point where they

TABLE 3-4

Constellation Size as a Function of α

$\alpha(km^{-1})$	Constellation Altitude (km)	Initial Constellation	Final Constellation
.01	4050.62	12	24
.02	3121.85	15	18
.03	3121.86	15	18
.04	3516.58	15	21
.05	2765.52	18	18
.10	2332.07	24	18
.20	832.00	77	20
.30	855.00	104	20
.40	770.63	160	20
.50	927.64	195 *	--
.60	939.29	252 *	--
.70	1076.00	280 *	--
.80	1140.30	396 *	--
.90	1205.85	598 *	--
1.00	1265.31	918 *	--

* Beyond Program Limits

Note: Baseline scenario with 500 missile attack force, minimum engagement altitude of 7.0 km.

could be used for space-based applications, the wavelength of the laser radiation could be selected to correspond to an optimum atmospheric "window". The unique feature of a free-electron laser is its ability to be "tuned" to any desired wavelength or frequency (Ref 8). Appendix A gives a detailed presentation of the HELSTAR simulations for constellation size versus α.

<u>The Investigation of the Effects of Minimum Engagement Altitude on the Final Constellation</u>

Since the minimum engagement altitude would effectively determine how much laser radiation would be absorbed or attenuated by the atmosphere, this aspect of HELSTAR might also be important. This was expected to be an interesting analysis since (if the minimum engagement altitude was high enough) even lasers with comparatively high values of atmospheric attenuation could deposit large amounts of radiation on the target surface; this is due to the effect of lower atmospheric densities at higher altitudes. However, as mentioned previously, this delay would also degrade the effectiveness of the system since targets can only be engaged during the boost phase (Ref 7:8).

Two separate analyses were performed, both using circular polar orbits. The first was performed using the lowest value of atmospheric attenuation ($\alpha = .058\ km^{-1}$) yielding the results depicted in Table 3-5. The second analysis was a study of the final constellation as a function of minimum engagement altitude using a higher value of α which would yield usable results. Again, due to computer resource limitations, $\alpha = .30\ km^{-1}$ was chosen — these results are given in Table 3-6.

Note that in Tables 3-5 and 3-6 there are some minimum engagement

TABLE 3-5

Final Constellation as a Function of Minimum Engagement Altitude

(α = .058 km^{-1})

Minimum Engagement Altitude (km)	Final Constellation	Constellation Altitude (km)
7.0	18	2876.04
10.0	21 (21)	3430.39
11.0	21 (21)	3342.75
12.0	24 (24)	3967.31
13.0	24 (24)	3762.13
14.0	21 (21)	3090.72
15.0	21 (21)	3092.00
20.0	24 (24)	3960.96
25.0	28 (28)	4315.53
30.0	28	4325.05
35.0	28	4333.36
40.0	32	4341.81
45.0	32	4349.88

Note: Baseline scenario with 500 missile attack force, 95% kill success criteria.

TABLE 3-6

Final Constellation as a Function of Minimum Engagement Altitude

($\alpha = .30\ km^{-1}$)

Minimum Engagement Altitude (km)	Final Constellation	Constellation Altitude (km)
7.0	20	855.00
10.0	18 (20)	995.69
11.0	18 (18)	1364.63
12.0	18 (18)	1753.99
13.0	18 (18)	1733.25
14.0	18 (20)	2011.22
15.0	20 (18)	2313.49
20.0	21 (21)	2857.51
25.0	24 (24)	3106.98
30.0	28	4088.12
35.0	32	4997.70
40.0	32	4341.63
45.0	32	4350.05

Note: Baseline scenario with 500 missile attack force, 95% kill success criteria.

altitudes with two entries for a final constellation (10.0 km, 11.0 km, etc.). For these particular simulations, the effect of the random number seed on the final constellation was examined. Throughout the entire study, a random number seed of 335971 was used, but for these particular altitudes the value of 335970 was used. Note that for $\alpha = .058\ km^{-1}$ there is no effect on the final constellation although for $\alpha = .30\ km^{-1}$ there are three cases wherein different final constellations are obtained; this does indicate the approximate nature of the final outcome. Users should be aware of the need to fully investigate all possible parameters when analyzing or recommending a particular laser system or basing mode.

The Analysis of the Effect of Minimum Orbital Altitude

It was thought that the minimum altitude of the orbiting laser would have some effect on the approximate optimum constellation. To accomplish this the circular orbit deployment mode with $\alpha = .058\ km^{-1}$ was chosen, and various minimum altitudes, ranging from 300 km to 9000 km, were examined. Table 3-7 was the result.

Notice that the final optimum constellation remains the same until 4000 km. At altitudes higher than this, the required number of lasers increases quite drastically. The reasons for this increase will be given in the next chapter but the system is following expectations -- the higher the minimum orbital altitude, the greater the number of lasers required to counter a given threat.

At the surface, the value of this particular analysis can be considered to be dubious at best. However, even though no value is apparent it does further the basic verification and validation efforts of this

TABLE 3-7

Final Constellation as a Function of Minimum Orbital Altitude

(α = .058 km^{-1})

Minimum Altitude (km)	Final Constellation (Rings/Lasers Per Ring)
300	3/6
400	3/6
500	3/6
600	3/6
700	3/6
800	3/6
900	3/6
1000	3/6
1500	3/6
2000	3/6
2500	3/6
3000	3/6
4000	3/7
5000	3/8
6000	4/8
7000	5/8
8000	6/10
9000	11/13 *

* Beyond Program Limits

study.

The Investigation of Time Dependent Launch Scenarios

As has been discussed, Hunter and Wysocki stated that simultaneous launches for the entire attacking missile force would result in a conservative estimate of the final SBL constellation. However, time limitations prevented them from proceeding with an analysis of this type in detail. To determine if this was a valid assumption, three types of scenarios, or launch sequences, were derived; resulting SBL constellations were then compared to the baseline scenario for any significant differences in effectiveness.

Launch Sequence 1. The launch sequence of active launch sites and their respective targets is given by Figure 3-2. Notice that five targets are attacked in the first strike: Washington, Castle, Beale, Pease, and Barksdale. All five are close to their respective seaboards and logic dictates that these five targets would be targeted by submarines on station near them. The second attack wave would be launched 30 minutes after the first strike to allow for damage assessment and necessary retargeting. The targets for these missiles would be in the "northern tier" of the United States. The third wave of missiles would be launched 45 minutes after the first wave -- note that their targets are in the central and southern regions of the United States. It should be emphasized that this is a purely hypothetical scenario -- although it does seem to be quite logical. Launch Sequence 1 is a time-phased launch from sites located throughout the Soviet Union. Such a scenario would be expected to require a large number of orbiting lasers in independent orbital rings due to the large land mass of the U.S.S.R.

Immediate Strikes

Target	Launch Time (sec)	Launch Site
Washington	0	23
Castle AFB	30	21
Beale AFB	30	22
Pease AFB	45	24
Barksdale AFB	60	25

Secondary Strikes

Loring AFB	1800	1
Ellsworth AFB	1800	11
Malmstrom AFB	1800	12
Wurtsmith AFB	1800	17
Griffis AFB	1800	4

Tertiary Strikes

Grissom AFB	2700	5
Little Rock AFB	2700	6
Whiteman AFB	2700	8
McConnell AFB	2700	14
Dyess AFB	2700	20

Figure 3-2. Launch Sequence #1.

Launch Sequence 2. In this sequence, one launch site was chosen to launch the entire strike force simultaneously. Such a strategy could also result in an inordimately large number of orbital rings/lasers per ring, since only a limited number of lasers would be in view of the single launch site (and thus be able to engage) at any one time. The pre-assigned success criteria could be a very sensitive parameter in this case.

For Launch Sequence 2, launch site 12 was selected due to its centralized location within the U.S.S.R. Centrality was desired to offset any unwanted effects geographical location might have on the simulation. Again, all 500 attacking missiles were launched simultaneously from one location to determine what effects this strategy would have on the resulting constellation, not because this reflects any real-world strategy or plan for action.

Launch Sequence 3. Launch Sequence 3 is a time dependent variation of Launch Sequence 2. Instead of the entire missile force being launched at one time, 200 missiles are launched at first, followed by 200 missiles 30 minutes later, and finally, 100 missiles at 45 minutes. One would expect this strategy to involve fewer rings and lasers than Launch Sequence 2 since the missiles would not be concentrated in time or space.

The results of these three scenarios are depicted in Table 3-8. Circular and elliptical orbits were examined using a laser system with an assigned value $\alpha = .058\ km^{-1}$; simulations were performed for 95% and 100% kill rates.

For certain simulations (notably Launch Sequence 1) results could not be obtained due to exceedingly long computer runs on the order of 10,000 seconds. It is noteworthy that the smallest final constellations

TABLE 3-8

Constellation Size as a Function of Launch Scenario and Basing

(α = .058 km^{-1})

Launch Sequence		Elliptical (Worldwide)	Elliptical (N. Hemisphere)	Circular (Polar)
1	95%	*	*	3/5
	100%	*	*	3/6
2	95%	7/16	7/16	3/5
	100%	7/16	7/12	4/9
3	95%	*	6/4	3/5
	100%	7/16	7/10	3/7

* Used excessive computer time.

obtained throughout this study occurred as a result of Launch Sequence 1 (three rings with five lasers per ring). And, Launch Sequence 2 resulted in one of the largest final constellations for circular polar orbits.

However, an error was found as a result of analyzing Launch Sequence 3. If any missiles from the first attack wave were able to leak through the defense system, all lasers exhausted their fuel supply within 300 seconds. Consequently, any missiles launched after this point were not engaged and were able to reach their assigned targets. This only occurred during Launch Sequence 3 scenarios.

Summary

This chapter has presented an overview of the tests and comparisons performed using HELSTAR. A baseline scenario was developed and certain "critical" parameters identified. Any analysis of the results presented in this chapter is, at best, superficial in nature; further analysis will follow in chapter four. The results depicted in numerous tables give the final approximate optimum constellation as a function of various control variables and parameters.

It should be noted that this research is directed toward verifying and validating the simulation model and can not recommend one particular laser system or basing scheme.

IV. The Analysis of the Results

HELSTAR is a very flexible model -- it is able to incorporate the many parameters and dynamic aspects of a laser defense system. To preclude performing an inordinate number of simulations, several key factors had to be identified and examined (see Appendix B). This chapter will analyze the results thus obtained and shed additional light on the dynamics of this type of defense system.

However, it should be emphasized at this point that this study was undertaken to further the verification and validation efforts of the HELSTAR model, not to recommend the validity or overall effectiveness of a space-based laser defense system. Although in the analysis of these results it might appear that one type of system is more effective than another, other aspects and technical problems must be considered before such a claim can be made.

HELSTAR is a model that represents certain situations given certain assumptions and approximations; by its very nature the optimal final constellation is only "approximate". Therefore, the question concerning user confidence in the model can never be adequately answered. If the model can give consistent, logical results, then user confidence should remain high; if counter-intuitive results appear, every effort must be made to determine if some error in the model has surfaced. The results of this study must be analyzed with these thoughts in mind.

The Comparison of Baseline Scenarios

When beginning this study, the need for some type of baseline scenario was immediately recognized. Unfortunately, the initial baseline

scenario with a 675 missile attack force, was found to require large amounts of computer time to run to completion. Since it would be necessary to make numerous computer runs in the course of this study, some way had to be found to reduce the size of the baseline. It was felt that the best way to do this would be to reduce the size of the attacking force. In doing so, the amount of time to complete the simulations was considerably reduced and led to an interesting comparison study.

These two baseline scenarios are depicted in Tables 4-1 and 4-2. For many of the cases involving large values of atmospheric attenuation (α), the program could not be initialized -- this was found to be a limitation of the program. For these cases, the program ran in excess of 5000 seconds while attempting to determine a value for atmospheric transmissivity, (T). For this reason, the 5.0 micron ($\alpha = 1.265\ km^{-1}$) system was not used in subsequent evaluations.

Also, for many of the cases, program limits for the number of orbital rings and lasers per ring were exceeded and program execution did not occur. These limits are:

number of rings (N) > 10

lasers per ring (M) > 20

After the program determines the initial constellation, the number of rings and satellites are compared with these limits and execution of the program either continues or terminates. If additional investigations are warranted into these "out of limits" cases, simple modifications to HELSTAR would be required.

Note that in almost every case, the constellations required to defeat the smaller attack force are themselves smaller. The single case

TABLE 4-1

Constellation Size as a Function of Laser Wavelength and Orbit Selection

(675 Missile Attack Force)

	ORBIT		
λ(μm)	Elliptical (1)	Elliptical (2)	Circular, Polar (3)
1.06	176 (4)	143 (4)	54
2.5	840 (4)	--- (5)	300 (4)
3.8	112	70	18
5.0	--- (5)	--- (5)	--- (5)
10.6	192 (4)	168 (4)	88

Notes:

1. Critically inclined, continuous worldwide coverage
2. Critically inclined, continuous northern hemisphere coverage
3. Continuous worldwide coverage
4. Beyond program limits after initialization
5. Did not initialize

TABLE 4-2

Constellation Size as a Function of Laser Wavelength and Orbit Selection

(500 Missile Attack Force)

	ORBIT		
$\lambda (\mu m)$	Elliptical (1)	Elliptical (2)	Circular, Polar (3)
1.06	176 (4)	143 (4)	18
2.5	840 (4)	--- (5)	300 (4)
3.8	30	24	18
5.0	--- (5)	--- (5)	300 (4)
10.6	192 (4)	168 (4)	20

Notes:

1. Critically inclined, continuous worldwide coverage
2. Critically inclined, continuous northern hemisphere coverage
3. Continuous worldwide coverage
4. Beyond program limits after initialization
5. Did not initialize

worthy of individual scrutiny is the case of circular polar orbits with $\alpha = .058\ km^{-1}$. For both baseline scenarios, this particular deployment required 3 rings of 6 lasers to defeat 95% of the missile force.

In all cases, the circular polar orbits yielded smaller, final constellations; this particular type of orbit also took less time to run to completion. For these reasons, the circular orbit constellation was chosen to be used for further investigation in the overall parametric study.

Of interest is the fact that a larger number of lasers are required to defeat a larger strike force; since these missiles are launched simultaneously, one would expect this to occur. Also, lower values of atmospheric, absorption consistently yielded smaller final constellations. This is a result of the amount of energy deposited on the target. Of course, the amount of energy deposited on the target missiles is attenuated only when the targets are within the atmosphere; when the missiles are in free space, the full amount of energy is deposited on the target vehicle and there is no difference between the five types of lasers.

So it would seem that the coefficient of atmospheric attenuation would have some effect on final constellation size. This was the first system parameter to be investigated in this study.

<u>The Effect of α on Final Constellation Size</u>

Table 3-4 presents the tabular data that resulted from this investigation. All of these simulations were run using the same standard scenario (minimum engagement altitude 7.0 km, random number stream, etc.) with atmospheric attenuation being the only factor that was varied. Simulations were run to completion using different values of α up to $.50\ km^{-1}$;

at this point automatic program limits were encountered and optimum constellations could not be obtained.

As can be seen, the resultant final constellations varied from 18 to 24 satellites. There was a slight variation of constellation size as a function of atmospheric attenuation, but there also appeared to be a counter-intuitive result -- for certain low values of α (supposedly very "efficient" systems) the resulting constellations were larger than those using a relatively higher value of α. This was counter intuitive: the higher values of α meant that less energy was deposited on targets within the atmosphere and therefore should have resulted in larger constellations.

For example, the two cases of $\alpha = .01\ km^{-1}$ and $\alpha = .02\ km^{-1}$ yielded constellations of 24 total lasers and 18 total lasers, respectively. To determine why this occurred, a detailed look at the structure of the algorithm must be undertaken.

When studying a circular polar constellation, two subroutines are used to determine laser system capabilities and to initialize the program (subroutines AMNRMX and POCICD). By specifying a minimum engagement altitude and a specific minimum intensity on the target at that altitude, a maximum theoretical range for the laser is determined. From this value, a specific altitude for the constellation is determined in subroutine POCICD.

Naturally, systems with small values of atmospheric attenuation are found to have a larger maximum tactical range (and therefore higher orbit altitudes), than those systems with larger values of α. This is so because radiation at lower α is transmitted better through the at-

mosphere. In our example, we find the following:

(km^{-1})	Maximum Tactical Range (km)	Altitude (km)	Final Constellation
.01	7838.51	4050.62	24
.02	6423.50	3121.85	18

The selection of orbit altitudes has an important impact on constellation effectiveness. Peak beam intensity is given by Hunter and Wysocki, eq. 3-1:

$$I(R) = I_{ref}\left(\frac{R_{ref}}{R}\right)^2 \qquad (4\text{-}1)$$

Here we have an inverse-square relationship as a function of range. Thus, all else being equal, systems that are at higher altitudes can be expected to deposit smaller quantities of energy on targets just out of the atmosphere than systems established in a lower orbit.

When one considers that many of these engagements are exoatmospheric (and therefore atmospheric attenuation would be negligible), constellation altitude becomes quite important. Realistically, an assigned orbital altitude might be a design parameter established by strategic planners or analysts. However, the HELSTAR model determines the optimum altitude for the constellation based on the initializing criterion to obtain worldwide coverage of some minimum intensity at the minimum targetable altitude. By using this initialization criterion, more capable weapons are placed at higher altitudes. However, this turns out to be a penalty for many of the engagements in the following simulations. This is an area where the HELSTAR model could probably be improved.

Since this inverse-square relationship, eq. 4-1, held true for all systems, low α systems would have less laser intensity deposited on

targets because of their higher orbits. This led to slightly larger constellations for these systems. And, for larger values of α, constellations began to grow due to the effect of atmospheric attenuation. The critical factor here is that HELSTAR, as now configured, determines the orbital altitude for these systems at initialization and this is a major factor in overall system performances.

As an overall observation, however, the model is performing as expected. The model can determine how much energy is deposited on target vehicles and is then able to simulate the resulting engagements through to completion. Perhaps this could mean several significant things to the planner who desires to use such a system to engage targets well within the atmosphere:

- given a system with low α, since it is relatively efficient it might use smaller output optics
- given a system with high α, low orbital altitudes would be necessary.
- high α systems could delay their engagements with target vehicles until higher altitudes are reached

The next investigation involves the last observation -- what effect would minimum engagement altitude have on overall system performance.

Analysis of the Effect of Minimum Engagement Altitude

The minimum engagement altitude is merely the lowest altitude at which the target missiles are attacked by the SBL constellation. As mentioned previously, there could be two effects resulting from an increase in the minimum engagement altitude.

We have already seen that at low altitudes laser radiation is at-

tenuated due to atmospheric absorption and scattering -- the greater the atmospheric density, the greater the scattering. It should therefore hold that at higher altitudes, the effect of this attenuation would be diminished due to lower atmospheric densities. Alternatively, we could carry this to the extreme and delay all engagements until all of the attacking missiles have exited the atmosphere; in free space there would be no atmospheric attenuation and any of the types of lasers should be equally effective. However, this would not be a sound strategy since we have given ourselves a definite time limit during which we can engage the attacking missiles (the boost phase); during this time period the missiles are assumed to be most vulnerable to this type of defense (Ref 7: 8).

So we see a unique trade-off developing. First, does minimum engagement altitude have any effect on constellation size; second, would this also be a function of atmospheric absorption; and third, can a minimum engagement altitude be found that "optimizes" constellation size?

For this particular analysis, two values of α were chosen for multiple simulations. The first ($\alpha = .058\ km^{-1}$) was chosen because we've already seen that by using it we are able to generate quite a few simulations in a relatively short period of time. The second value, $\alpha = .30\ km^{-1}$, was chosen because it was felt that a relatively large value of α was necessary and yet should yield usable results in a relatively short period of computer time. It was found that $\alpha = .30\ km^{-1}$ was able to fulfill these requirements. The results of these multiple simulations are depicted in Tables 3-5 and 3-6.

Note that for $\alpha = .058\ km^{-1}$, the results are slightly non-uniform, although there does appear to be a linear relationship between minimum engagement altitude and final constellation size (see Fig. 4-1). This relationship is due to the decreased amount of time available to engage the attacking missile force at higher minimum engagement altitudes. There is a slight discrepancy at minimum engagement altitudes of 12 and 13 kilometers. Here we found slightly larger constellations than at 11 km and 14 km -- this is due to the slightly higher constellation altitudes derived by the HELSTAR program for these scenarios. HELSTAR altitudes will be discussed shortly.

For $\alpha = .30\ km^{-1}$ (see Fig. 4-2), we see that the number of required SBL's to defeat 95% of the attacking force remains fairly constant at about 18 lasers until we specify minimum engagement altitudes above 25 km. Indeed, when comparing both $\alpha = .30\ km^{-1}$ and $\alpha = .058\ km^{-1}$, we find that the former system is more "efficient" than the latter. This is due to the effect of the constellation altitude as derived by the HELSTAR initialization algorithm. Comparing constellation altitudes (Tables 3-5 and 3-6), we find that the system that is least affected by atmospheric attenuation is placed at a higher altitude and thus is more affected by the inverse-square propagation of laser intensity during simulated engagements (eq. 4-1).

So, we find from these comparisons that the minimum engagement altitude does have an effect on the size of the final constellation and the atmospheric attenuation effects are also quite important. To make a truly accurate comparison between the two systems with different α, however, each should be evaluated at the constellation altitude "best" for it. The ability to specify an assigned altitude is a modification to

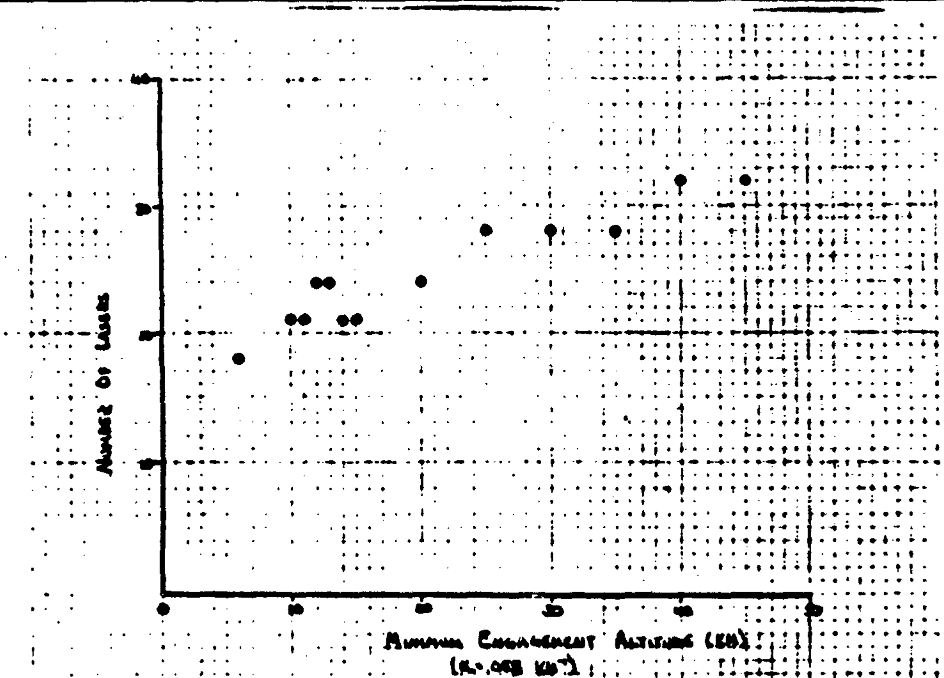

Figure 4-1.

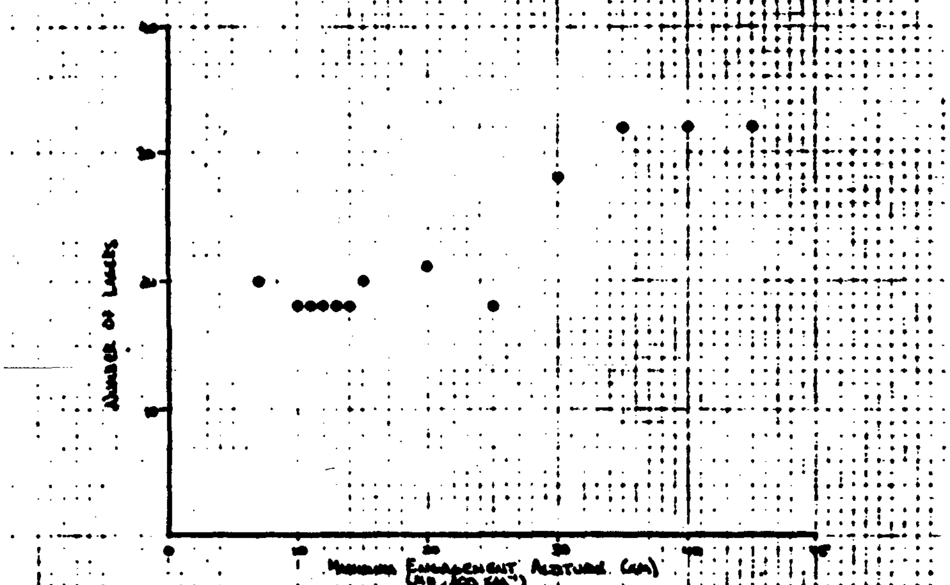

Figure 4-2

Figures 4-1 and 4-2. Constellation Size as a Function of Minimum Engagement Altitude.

HELSTAR that hopefully will be made at a later date.

Also, for $\alpha = .30\ km^{-1}$ we find that there were three cases in which a different random number seed produced three different final constellations (minimum engagement altitudes of 10.0, 14.0, and 15.0 kilometers). This occurred for $\alpha = .30\ km^{-1}$ but not for $\alpha = .058\ km^{-1}$. An investigation was undertaken to determine if these particular cases can statistically be considered to be different.

<u>ANOVA</u>. An analysis of variance was undertaken to investigate the effects of the random number seed (335971 vs. 335970) for the scenarios represented by $\alpha = .300\ km^{-1}$ and minimum engagement altitudes of 10.0 km, 14.0 km, and 15.0 km.

For the first case, random number 335971 resulted in an analysis of a constellation of 4 rings with 5 lasers per ring for the ninth battle scenario; random number 335970 yielded an analysis of the same size constellation for its ninth battle scenario. However, in the former case, the algorithm determined that a 20 satellite constellation did not meet the 95% success criteria and continued to iterate through two additional constellations. The end result was a final constellation of 18 satellites for the original random number seed, and a constellation of 20 satellites for the second random number seed. An analysis of variance was therefore undertaken to examine the mean number of missile kills that resulted from these identical constellations.

In performing ANOVA, there are seven observations with two different treatments with an F value of

$$F = 2.02$$

For $\alpha = .10$,

TABLE 4-3

Comparison of Ninth Scenario Analysis

Minimum Engagement Altitude 10.0 km

Battle	335971	335970
1	486	500
2	497	491
3	499	482
4	496	470
5	478	500
6	495	463
7	493	477
Mean	492.0	483.3
S.D.	7.4	14.4
Var	47.4	178.2

Note: Four orbital rings/five lasers per ring.

$$F_{.10,1,12} = 3.18$$

Since the computed F-value is less than 3.18, the two means (μ_1 = 492.0 and μ_2 = 483.3) can be considered to be statistically equal. Therefore, one can argue that the two random number seeds generated constellations that are equally effective for this particular minimum engagement altitude.

In a similar manner, the battles for 14.0 and 15.0 km were searched for identical constellations and the mean battle kills were determined and analyzed. For 14.0 km,

$$F = 6.77$$

and 15.0 km yielded

$$F = .01$$

For 14.0 km the computed F value indicates that these means cannot be considered to be equal at an α level of .10. If the computer products are examined for the 14.0 km minimum engagement altitude, we find that there is considerable difference between the two simulations; random seed number 335971 yielded a variance of 5.55 versus 55.3 for seed number 335970. We can conclude that for this particular minimum engagement altitude, there is significant difference between the two simulations.

These figures merely indicate the approximate nature of the final constellation. It appears that the random number stream used in the algorithm could have an effect on the final constellation size. If anything of value is to be gained from this exercise, it is that thorough analysis of any particular laser system or basing scheme must be performed before any one system can be recommended over another.

The Effect of Minimum Orbital Altitude on the Final Constellation

The minimum orbital altitude is specified as one of the battle management parameters and the effect of it on the final constellation size was investigated (Table 3-7). As can be seen from the results, the final constellation size was not affected by this parameter until approximately 4000 km. This was due to the effect of maximum effective range of the laser system.

For all constellations up to 4000 km, the maximum effective range of this particular laser system allowed the system to be assigned to an orbital altitude of 2876.04 km. Obviously, this was greater than the specified minimum altitudes and therefore all of these simulations were identical.

The final constellation size was not affected until a minimum orbital altitude on the same order as the maximum effective range of the laser system was specified. After this point had been reached, additional satellites were required to counter a given threat. Actually, this behavior is quite reasonable since the laser would be operating at the extreme limits of its ability. Of course, this argument assumes that during battles, engagements will occur down to the minimum altitude of 7.0 km and the effect of atmospheric attenuation then becomes quite apparent.

There were some discrepancies in this analysis, however. It was found that the assigned altitude for several constellations was less than that specified (2876 vs 3000 km, 3393 vs 4000 km, and 4345 vs 5000 km). This is a result of the iterative nature used in determining the initial coverage angle (BETMIN) and constellation altitude. The in-

terested observer is referred to subroutine AMNRNX.

The Effect of Atmospheric Attenuation on Computed Constellation Altitude

When studying the effect of atmospheric attenuation it was noted that the constellation altitude varied. As has been previously discussed, this is a result of the program establishing the altitude based on atmospheric transmissivity and specified energy deposition on the target vehicles. Since this altitude cannot be specified by the user and is computed by the program, an investigation was undertaken to examine how it varied as α was changed. Appendix C offers an explanation of the altitude determination algorithm used in HELSTAR.

As can be seen from Figure 4-3, this is not a smooth, continuous relationship. Initially, for relatively low values of α, we find that we have correspondingly high constellation altitudes. The altitude appears to decrease as attenuation increases, until values of .20 km^{-1} to .40 km^{-1} are reached; thereafter, constellation altitude begins to increase again.

Notice however, the discontinuous behavior of the plots, i.e., the large difference in altitude between α = .017 km^{-1} and α = .018 km^{-1}. Initially, it was felt that this was not conforming to the expected behavior of the model. True, a gradual decrease in constellation altitude as α increases can be explained, but large altitude discrepancies apparently do not conform to this expectation. Accordingly, a detailed examination of the HELSTAR model was undertaken.

For polar, circular orbits the determination of the size and configuration of the initial constellation is determined in subroutine POCICD using the maximum theoretical range of the weapon (RMAXC) and

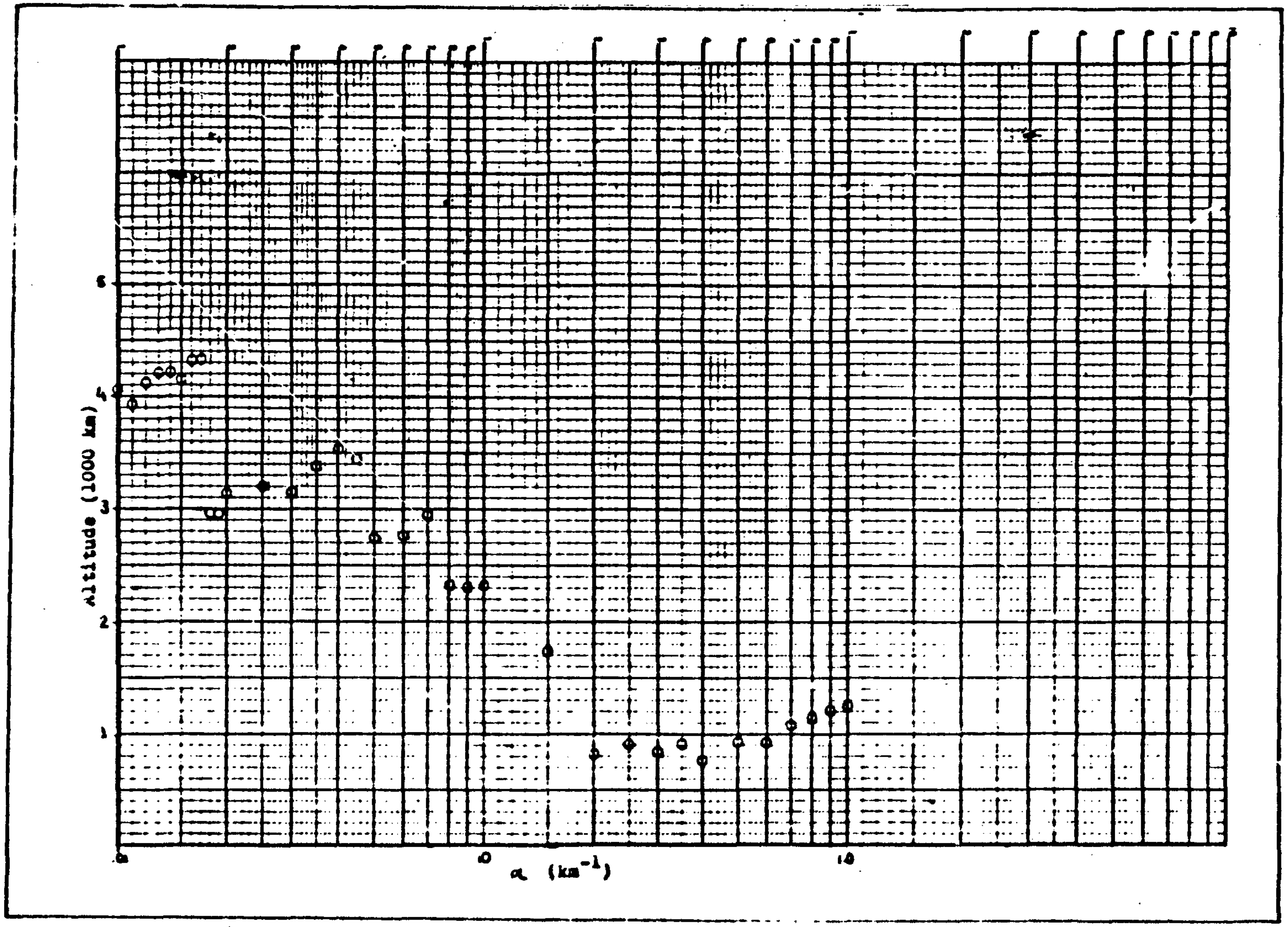

Figure 4-3. Constellation Altitude as a Function of Atmospheric Attenuation.

the beam angle of attack (BETMIN) at the minimum engagement altitude. The maximum theoretical range and beam angle of attack are computed by subroutine AMNRMX based on placing a single weapon at an altitude which maximizes the coverage circle within which the weapon can place the minimum energy at the minimum altitude. Using these values, POCICD begins to initialize the program by determining the constellation altitude (actually ABSR, the sum of the earth's radius and the altitude of the constellation) and the number of orbital rings, M, and the lasers per ring, N. The subroutine must perform a number of iterations to develop optimal integer values for M and N; in doing so, M and N are rounded to integers which are then used to recompute a new value of constellation altitude.

So, when investigating the altitude of a given constellation, it should be remembered that it was determined by an iteration process to integerize M and N and thus subject to discontinuities. Conversely, it would be instructional to investigate the parameters RMAXC and BETMIN as that are passed to subroutine POCICD and determine what value of constellation they would yield if no approximations had taken place in the iterating algorithm.

By using the values of RMAXC and BETMIN generated by AMNRMX and the relation

$$ABSR = [RMAXC^2 + (RE+AMIN)^2 + 2(RMAXC)(RE+AMIN)\sin BETMIN]^{1/2}$$

where AMIN = minimum engagement altitude (7.0 km), Figure 4-4 was derived. Notice that there appears to be considerable smoothing of these data plots; there does not appear to be any major discontinuities as we have seen before. Between the values of $\alpha = .010\ km^{-1}$ and $\alpha = .30\ km^{-1}$,

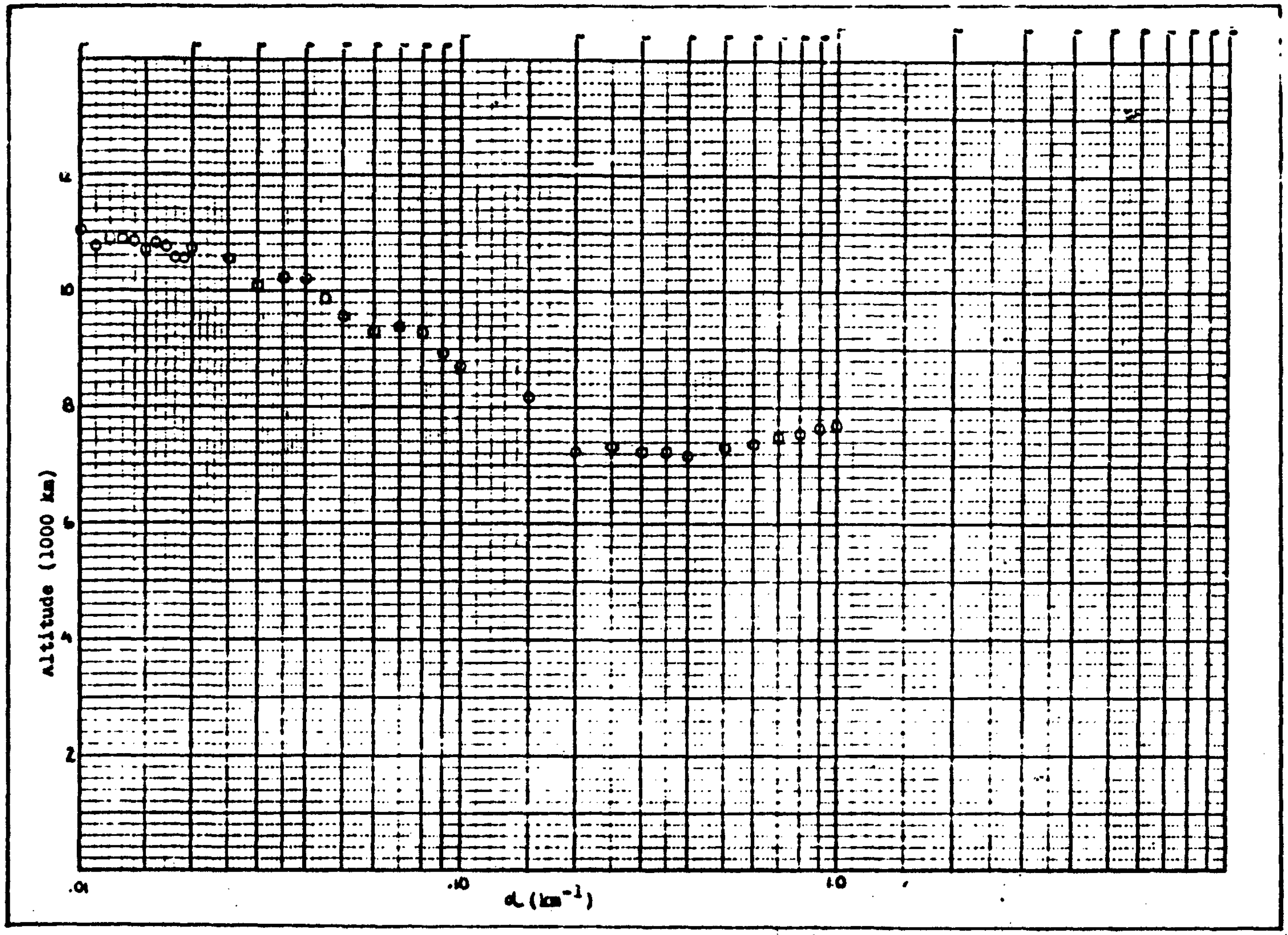

Figure 4-4. ABSR as a Function of Atmospheric Attenuation.

we can see that the plots are decreasing as a function of α with no "jumps" or unexplained values.

In summary, we find that there does appear to be a relationship between the altitude of the constellation and the coefficient of atmospheric attenuation for the laser radiation. There does appear to be a discontinuous relationship but in examining the functional workings of HELSTAR this is a result of an iterative algorithm to integerize the number of lasers in orbit.

The minimum constellation altitude is attained for values of atmospheric attenuation between .20 km^{-1} and .60 km^{-1}. Beyond $\alpha = 1.0$ km^{-1}, large quantities of computer time were used and initialization of HELSTAR was not obtained. Atmospheric transmissivity was quite difficult to compute with these values of α and no further attempts were undertaken to investigate these areas.

An Analysis of Time-Dependent Launch Sequences

As discussed previously, one of the objectives of this research effort was to determine what effect a time-phased launch would have on the overall constellation size. It was thought that a simultaneous launch would lead to a larger constellation size since this would, in effect, be testing the system to its limits. If the missiles are launched over a period of time (on the order of 45 minutes) it was felt that smaller, final constellations would result.

Also, in this same vein, could some combination of launch site and launch time be found which would considerably stress the system? It was with these objectives that an investigation of Launch Sequences 1, 2, and 3 was undertaken.

Launch Sequence 1. This sequence represents a more "plausible" attack scenario than those previously studied wherein the entire missile force is launched simultaneously. Certain priority targets were chosen for an immediate strike followed by a second attack after time had allowed for damage assessment, and finally a third attack finished the sequence.

Table 3-8 illustrates the results thus obtained. Comparing this table with Table 4-2 we see that the 95% success criteria results in a constellation of 15 satellites, which is approximately 16% less than the 18 satellite constellation obtained by the 95% baseline scenario. An attempt was made to analyze the two elliptical basing modes but due to exessive time requirements, no results were obtained.

It is interesting to note that the constellation requirements for Launch Sequence 1 followed previously established expectations. If the missiles are launched from a large geographical area and over a long period of time, then they are more likely to be engaged by "dormant" SBL's. Consequently, kill rates are higher which would result in smaller final constellations. This was verified by a detailed inspection of the individual battle statistics.

Conversely, what would occur if only a few SBL's were able to engage the attacking force? Would a larger constellation result and how could this scenario be modelled? Launch Sequence 2 was derived to examine this possibility.

Launch Sequence 2. This sequence models the likely outcome of all missiles being concentrated in one site and being launched simultaneously. In doing so, only a small number of SBL's would be eligible to engage the

missile force -- stressing the defense system even more than the initial baseline scenario.

As can be seen from Table 3-8, Launch Sequence 2 resulted in a larger constellation than Launch Sequence 1, both for the 95% and 100% kill success criteria. In fact, this particular scenario resulted in the largest final constellation of all circular orbits (using $\alpha = .058$ km^{-1}) studied.

A limited engagement "window" did indeed result in a larger final constellation, whereas a wider engagement "window" lead to smaller constellations. On a grander scale, one can assume that a larger, concentrated attack force would require as even larger SBL constellation.

Indeed, in keeping with previous findings and trends, we note that the two elliptical constellations again result in larger constellations than the circular, polar orbit configuration.

<u>Launch Sequence 3</u>. As a further effort towards verification and validation, Launch Sequence 3 was developed. In this sequence, all 500 missiles are launched from the same launch site as in Launch Sequence 2, but their launches are phased over a period of time, as in Launch Sequence 1. In this case, one would expect a smaller number of SBL's (as compared to Launch Sequence 2) would be required to cope with the threat since the missiles are engaged over a longer period of time. Conversely, one might expect the resultant constellation to be larger than that of Launch Sequence 1 since in 1 the missiles are concentrated in one location and therefore engaged by a smaller number of SBL's.

The results in Table 3-8 for the circular polar constellation confirm these expectations. Again, due to longer processing times, valid

results could not be obtained for some elliptical constellations and therefore no comparisons can be made with the other two launch sequences.

The analysis of these three launch sequences tend to substantiate the assumptions made by Hunter and Wysocki concerning the simultaneous launch of the strike force resulting in more conservative estimates of constellation size. Concentrated, mass launches result in large constellations; missiles launched over a period of time and a large geographical area result in relatively smaller constellations.

For a truly accurate analysis of any "realistic" attack scenario, one would have to assign each individual missile as a cell of one, with it's unique launch time. The computational efforts required for an attack force of moderate size can become quite large. For this reason, these three generalized scenarios were developed to determine if the model is performing as expected.

These sequences are purely imaginary, designed and used for illustrative purposes only and reflect no known (or surmised) knowledge of planned strategic exchanges.

An Investigation of SBL Altitude and Size as Functions of IMIN and α

In their original work, Hunter and Wysocki noted (Ref 7: 59):

> during the course of model development, a relationship was noted between the selection of IMIN and the altitude, size, and performance of the initial design constellation. It is recommended that the user conduct limited sensitivity analysis on the selection of IMIN for the particular system being modeled.

Therefore an investigation was undertaken to determine how SBL altitude and initial size would vary as a function of IMIN and atmospheric attenuation.

To accomplish this three values of α were chosen (.058 km^{-1}, .196

km^{-1}, .300 km^{-1}) and initial constellations were determined as IMIN was increased. Table 4-4 and Figure 4-5 show the results.

As expected, lower values of atmospheric attenuation resulted in higher constellation altitudes, and smaller initial constellations. It was generally found, however, that these initial constellations rarely were found to be the optimal final constellation. Generally, large initial constellations were found to be effective against 100% of the strike force and several iterations were required to reduce the constellation to just achieve the specified 95% success criteria. Systems with atmospheric attenuation coefficients on the order of .30 km^{-1} to .40 km^{-1} were found to be very effective due to their lower altitudes.

In general, Figure 4-4 indicates that constellation altitude for α = .058 km^{-1} tends to decrease as IMIN increases. This is easily explained by the inverse-square relationship for laser propagation previously discussed. And, we can see that constellation altitudes for systems with higher values of α tend to remain at the same altitude as I_{MIN} increases. Again, the inverse-square relationships for laser propagation can explain this tendency; since the SBL's are not located very far from their designated targets, small changes in I_{MIN} do not result in large changes in constellation altitude.

As previously noted, the constellation altitude was derived by an iterative algorithm and round-off errors will be evident in these figures. If HELSTAR could be modified to incorporate an altitude assignment capability, then valid comparisons could be made between these types of systems. It has been demonstrated that altitude has a very critical relationship (via the inverse-square propagation of laser radiation) on over-

TABLE 4-4

α	I_{MIN} (w/cm^2)	Altitude (km)	Initial Constellation
.058	75	3704.11	3/5
.058	80	3028.14	3/6
.058	85	2875.96	3/6
.058	90	2876.04	3/6
.058	95	2764.74	4/5
.058	100	2764.81	4/5
.058	105	2075.07	4/6
.300	75	972.69	8/11
.300	80	710.61	10/13
.300	85	660.41	10/14
.300	90	855.00	8/13
.300	95	723.40	11/13
.300	100	766.90	10/13
.300	105	826.15	9/13
.196	75	1376.58	6/8
.196	80	1411.90	6/8
.196	85	978.92	8/9
.196	90	1220.54	6/9
.196	95	1088.40	6/10
.196	100	952.70	7/10
.196	105	1046.86	8/9

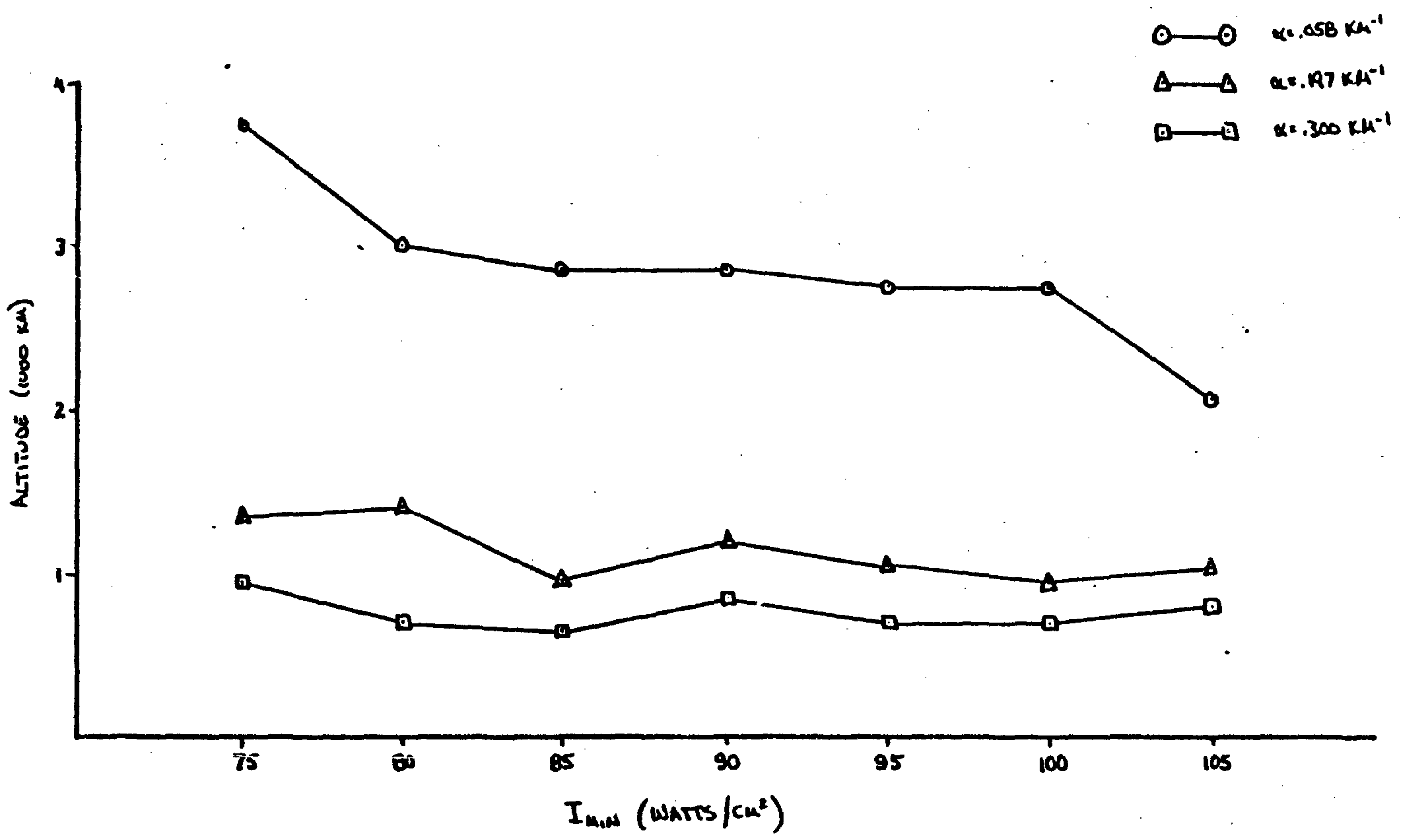

Figure 4-5. Constellation Altitude as a Function of I_{MIN}.

all system performance -- it's effects cannot be neglected.

An Investigation of the Effects of Identification Time

During the formulation of the baseline scenario, the type of identification and warning system to be used by the SBL defense had to be formulated and incorporated into the model. The HELSTAR program can simulate three separate identification systems using identification times drawn from a normal distribution, a uniform distribution, or by using a specified constant interval.

Since no information was available concerning the capabilities of such a subsystem, some arbitrary figure (or distribution) had to be chosen. Rather than attempting to justify a 90-second system, or a 75-second system (or any other type of system), an automatic and almost instantaneous system was chosen to be incorporated into the baseline scenarios. This type of identification system can not be defended as being any more "realistic" than any other under consideration; in fact, it would be a remarkable and very capable system is it could be designed and built. However, an identification system had to be chosen and an automatic system was thought to be as good as any other.

To determine what effect this might have had on the resultant final constellation, a comparison was made to a uniformly distributed identification time (60 to 90 seconds) for a number of selected scenarios. The four scenarios selected are:

- Baseline (circular orbits, $\alpha = .058\ km^{-1}$, 95%)
- Launch Sequence 1 (circular orbits, 95%, 100%)
- Launch Sequence 2 (circular orbits, 95%, 100%)
- Launch Sequence 3 (circular orbits, 95%, 100%)

The effects of identification time on the final constellation are given in Table 4-5.

As can be seen, the effect of a uniformly distributed (60 - 90 sec) identification and warning time is a tendency toward larger constellations. There were several cases where the final constellation was not affected by this change in identification times, but overall there was a definite tendency towards larger constellations.

Upon further examination of the computer printouts, the total time for battle completion was found to be longer (60 - 90 sec) for uniformly distributed ID times than for the automatic/instantaneous baseline cases. These battles were generally found to last from 10 to 25 seconds longer than the baseline situations. In all, this tends to follow intuition -- longer delays in the system due to a different type of identification system should lead to longer battles and longer constellations.

In summary, lag in the MW/AA/C^3 capability of the SBL defense system would probably lead to larger constellations in order to assure a given level of defense. Again, the reader is warned that this particular exercise was undertaken to gain some insight into the effect of a TW/AA/C^3 lag on the system. Aside from a tendency toward slightly larger constellations and longer battles, not much can be said about the effect of this factor on the overall system performance. When a particular system is designed and its performance and capabilities determined, considerable sensitivity analysis will then have to be performed to determine the effect of it on overall system effectiveness.

Summary

In summary, the analysis of a systematic parametric investigation

TABLE 4-5

Comparison of Instantaneous Identification Times

and Uniformly Distributed Identification Times

on Constellation Size

	Identification Time	
Scenario	Instantaneous	Uniform Distribution (4)
Baseline	18	21
Launch	15 (1)	15 (1)
Sequence 1	18 (2)	-- (3)
Launch	27 (1)	32 (1)
Sequence 2	36 (2)	36 (2)
Launch	15 (1)	18 (1)
Sequence 3	21 (2)	18 (1)

Notes:

1. 475 missile kill success criteria
2. 500 missile kill success criteria
3. Could not initialize
4. 60 - 90 seconds

of HELSTAR has been presented. Certain parameters have been investigated to determine their overall effect on the system in order to further verify and validate this model. Several model limitations have been found but generally the results have proved to be true to intuition and logical in their effects. The following is a brief summation of the main investigations performed during the course of this study.

Baseline Scenarios. A baseline scenario had to be developed, thereby establishing a "standard" by which changes in system performance could be measured. The chosen scenario involved an attacking force of 500 missiles launched from 15 sites spread evenly over the Soviet Union, Atlantic Ocean, Pacific Ocean and the Gulf of Mexico. Included in this baseline were the results of using five different types of lasers in three different orbital basing modes. The most efficient system was found to be one using a polar, circular orbit and a laser wavelength of 3.8 microns ($\alpha = .058\ km^{-1}$).

Effect of α on Constellation Size. By making numerous simulations with varying values of atmospheric attenuation, final constellation size and effectiveness was found to depend on constellation altitude. Final constellation altitude is, in part, determined by atmospheric attenuation. Low values of α result in constellations established in relatively high orbits and due to the physics of laser propagation, are not as effective as constellations placed in lower orbits. This is a model limitation which should be eliminated.

Effect of Minimum Engagement Altitude on Constellation Size. By raising the minimum engagement altitude, less capable systems (i.e., relatively high values of α) were found to be more efficient than low α

systems. However, as the minimum engagement altitude was increased, constellation altitude also began to increase with a consequent drop in efficiency and increase in constellation size. Overall, it was found that altitude determination was the result of an iterative algorithm subject to numerous round-off errors. Potential users should be aware of this and conduct limited sensitivity analysis on the effect of altitude on constellation effectiveness.

Effect of Minimum Orbital Altitude on Constellation Effectiveness. It was foun hat specified minimum altitudes less than the maximum effective r nge of the laser (RMAXC) had no effect on the constellation. For these cases, it was found that the actual constellation altitude was always higher than the minimum altitude specified as one of the battle management parameters. The constellation was affected only when the specified minimum altitude was greater than the maximum effective range of the laser.

The Effect of α on Constellation Altitude. Low α systems can be considered to be very "efficient" systems since attenuation effects in the atmosphere are quite low. Therefore, in designing the constellation, the HELSTAR program assigns these types of lasers a very high altitude to get the same intensity on target as a laser system with high α in a lower orbit. Problems arise when these systems engage their targets exo-atmospherically where there are no attenuation effects. As a result of this altitude difference, the low α systems (in the higher orbits) deposit less energy on their targets than those lasers assigned to a lower orbit. Consequently, the more efficient satellites in these lower orbits usually have smaller constellations. The analyst has no control over the

orbital altitude -- it is determined by system parameters during program initialization and has a significant effect on system efficiency. Since it has such an effect on system performance, it should be a battle management parameter to be specified by the analyst.

Time Dependent Launch Sequences. The baseline scenarios were constructed and analyzed using simultaneous launches of the entire strike. The assumption behind this type of strategy is that this places a burden on the system and leads to a more conservative constellation. Accordingly, Launch Sequence 1 was designed wherein the missile force is launched from the same launch sites but over a period of 45 minutes. The result was a small constellation since more SBL's were, in effect, able to engage the attacking force. Launch Sequence 2 was derived to determine what effect a "concentrated" missile force would have on the final constellation. In this case, all missiles were launched from the same site at the same time and the result was the largest constellation of all three sequences. Launch Sequence 3 was a combination of Sequences 1 and 2 -- 500 missiles launched from the same site, but over a period of 45 minutes. The resulting constellation was larger than Sequence 1 but smaller than Sequence 3. In all cases, the results were those that were anticipated.

Effect of I_{MIN} and α on the Initial Constellation. This was a parametric analysis to see what would happen to the initial constellation as I_{MIN} and α were varied. It was found that for low α laser systems, constellation altitude was more effected by I_{MIN} than high α systems. This was a result of the inverse-square law of laser propagation and the relative altitudes of the systems.

Effect of Uniformly Distributed ID Times on the Final Constellation. It was determined that this parametric analysis should contain an investigation into the effects of a longer delay in the $MW/AA/C^3$ time. The baseline scenario was a small ID time which translates into an automatic, instantaneous system. To make this comparison, identification times were to be chosen from a uniform distribution, between 60 and 90 seconds. In all, there was a tendency for slightly larger constellations and slightly longer times to complete individual battles.

In summation, it seems that the HELSTAR model does simulate the dynamic aspects of a SBL ballistic defense missile system -- at least in the areas where these investigations were performed.

V. Conclusions and Recommendations for Further Analysis

HELSTAR is a program that can model the complex physical phenomena associated with a laser defense system. As with any model of this nature, verification and validation is a different undertaking never fully achieved. The results of the previous chapters are an effort to help address this issue and to build the user's confidence that the model accurately portrays the interacting phenomena of a space-based laser defense system.

One of the findings of this investigation is that additional work is still needed in the investigation and refinement of the HELSTAR model. During the course of this study, it was found that the altitude of the laser system was quite critical to the overall effectiveness of the system -- so critical in fact, that supposedly "efficient" laser systems were found to be degraded because they were positioned at relatively high altitudes during initialization. To make an accurate comparison between two different types of laser systems or basing schemes, constellation altitude should be a control variable so that the propagation of laser intensity won't be affected by altitude differences.

Therefore, HELSTAR should be modified to include satellite altitude as one of the battle management parameters. By doing so, analyses similar to those presented in this work could be performed and direct comparisons made between two different systems. This would help to further verify and validate the model and build user confidence. After this modification has been made, further studies could be performed to determine the optimum altitude at which this type of system should be established. Con-

sequently, sensitivity analyses could be performed on such parameters as minimum engagement altitude and minimun intensity.

As mentioned in chapter three, in the final stages of this research effort, an error in the program was discovered as a result of Launch Sequence 3. Briefly, if any missiles were able to leak through the defense system, all lasers exhausted their fuel supplies within 300 seconds. Time did not allow for the determination of why this occurs or where the error is located. It was determined that this only occurs during Launch Sequence 3 and only if any missiles leak through on the first attack wave. Obviously, additional effort is required in this area.

Conclusions

HELSTAR is a model that can be used to gain insight into the dynamics of a SBL missile defense. As such, its final "optimum" solution is neither final nor optimum; as stated previously, it is "approximate". By using HELSTAR an appreciation can be gained into the interrelating processes in this type of system.

Overall, the effect of constellation altitude was found to be quite critical, as were the effects of atmospheric attenuation, type of constellation orbit, launch time, and launch location. For any type of exacting analysis, these parameters must be specified.

But, as with any simulation, this is an approximation of a complex process; HELSTAR cannot completely simulate an entire laser defense system in exact detail. During the course of this investigation, a critical limitation of the model was discovered. The inability to specify constellation altitude as a battle management parameter or to allow altitude to vary in the search for an "optimal" constellation are distinct limitations

of the model. The model has the ability to determine an "optimum" altitude but the inability of the user to specify a constellation altitude resulted in a unique altitude for each set of battle management and laser system parameters.

The error discovered during the analysis of Launch Sequence 3 would only affect scenarios of that type. This error needs to be corrected. Until this is done, Launch Squence 3 scenarios should be viewed as suspect unless detailed examination of the computer products is conducted. Further research into the structure of HELSTAR and familiarity with it will undoubtedly rectify the limitation and error.

During the course of this investigation, numerous simulations were not completed due to program limits or excessive time used in certain subroutines. It appears that not much was gained by these "failures". However, some knowledge was gained in finding these particular "limitations" of HELSTAR. This is, in effect, furthering the verification and validation of this model.

Many of the results produced by HELSTAR were foreseen and predictable thus building some degree of user confidence. When counterintuitive or unexpected results were produced, further investigations into the actual structure of HELSTAR were deemed necessary. After analyses (including manual calculations) were performed, these counterintuitive results were shown to be logical and accurate. This usually led to insights into the space-based laser defense mission.

For the efforts undertaken in this study, except for the anomalous behavior found in Launch Sequence 3, HELSTAR has generated logical, verifiable results. Further effort is needed in various areas of the

model, as previously mentioned, but HELSTAR does appear to be quite reliable and efficient in most areas. Again, it must be emphasized that this study was not an investigation into the effectiveness of a space-based laser defense system. Rather, it was an investigation of the HELSTAR model -- most results indicate that it can be used to evaluate these types of systems with a high degree of confidence.

Appendices

Appendix A

Constellation Size as a Function of Atmospheric Attenuation

This appendix is an example of the HELSTAR output used in this study. For each value of α the following is given:

- constellation altitude
- constellation size (orbital rings/lasers per ring)
- mean and standard deviation of missile kills
- final approximate optimum solution

As an example, consider the constellations analyzed for $\alpha = .01\ km^{-1}$. HELSTAR has computed that this constellation should be placed in an orbit with an altitude of 4050.2 km, the initial constellation contained three orbital rings with four lasers per ring, it had a mean kill of 321 missiles and a standard deviation of 17.3 missiles. For this particular constellation we also find that 154 missiles were not destroyed ("leakage") and the success criteria of 475 missiles was not satisfied.

Since the success criteria was not met, additional lasers are added to each orbital ring, and finally, more orbital rings are added in order to increase the performance of the system. This process continues until the success criteria has been met.

All of these constellations have been analyzed using the same baseline scenario and attack force:

- circular polar orbits
- 500 missile attack force
- 15 launch sites
- 475 missile kill success criteria

- same random number seed

However, even though these constellations are identical in many respects, note the effect atmospheric attenuation has on the constellation altitude. We find that as α increases, constellation altitude decreases which eventually results in a more effective system. Of particular interest is the constellation with $\alpha = .40\ km^{-1}$. We find that a large constellation is initially designed which is very effective. It is so effective that 16 iterations must be analyzed before any leakage occurs. This is a direct result of the relatively low orbital altitude.

The final approximate optimum constellation is designated with a single asterisk (*) and initial constellations beyond program limits are denoted with a double asterisk (**).

Constellation Size as a Function of Atmospheric Attenuation

$\alpha = .01\ km^{-1}$ Constellation Altitude = 4050.62 km

Constellation	Mean Kills	Leakage	Sigma
3/4	321	-154	17.3
3/5	380	-95	14.4
3/6	431	-44	11.6
4/5	470	-5	12.3
4/6 *	494	+19	5.1
4/5	470	-5	8.6

$\alpha = .02\ km^{-1}$ Constellation Altitude = 3121.85 km

Constellation	Mean Kills	Leakage	Sigma
3/5	411	-64	24.1
3/6 *	482	+7	11.9

$\alpha = .03\ km^{-1}$ Constellation Altitude = 3121.86 km

Constellation	Mean Kills	Leakage	Sigma
3/5	410	-65	23.6
3/6 *	481	+6	11.7

$\alpha = .04\ km^{-1}$ Constellation Altitude = 3516.58 km

Constellation	Mean Kills	Leakage	Sigma
3/5	389	-86	22.5
3/6	465	-10	18.5
3/7 *	494	+19	5.1
3/6	461	-14	13.0

$\alpha = .05\ km^{-1}$ Constellation Altitude = 2765.52 km

Constellation	Mean Kills	Leakage	Sigma
3/6 *	490	+15	5.0
3/5	432	-43	15.8

$\alpha = .10\ km^{-1}$ Constellation Altitude = 2332.07 km

Constellation	Mean Kills	Leakage	Sigma
4/6	500	+25	0.0
4/5	496	+21	6.8
3/5	452	-23	15.2
3/6 *	499	+24	2.7
3/5	443	-32	10.9

$\alpha = .20\ km^{-1}$ Constellation Altitude = 832.00 km

Constellation	Mean Kills	Leakage	Sigma
7/11	500	+25	0.0
7/10	500	+25	0.0
7/9	500	+25	0.0
6/9	500	+25	0.0
6/8	500	+25	0.1
5/8	500	+25	0.0
5/7	500	+25	0.0
4/7	500	+25	0.0

(α = .20 km^{-1} cont'd)

Constellation	Mean Kills	Leakage	Sigma
4/6	500	+25	0.0
4/5 *	481	+6	19.5

α = .30 km^{-1} Constellation Altitude = 855.00 km

8/13	500	+25	0.0
8/12	500	+25	0.0
8/11	500	+25	0.0
8/10	500	+25	0.0
7/10	500	+25	0.0
7/9	500	+25	0.0
6/9	500	+25	0.0
6/8	500	+25	0.0
5/8	500	+25	0.0
5/7	500	+25	0.0
4/7	500	+25	0.0
4/6	500	+25	0.4
4/5 *	486	+11	11.0

α = .40 km^{-1} Constellation Altitude = 770.63 km

10/16	500	+25	0.0
10/15	500	+25	0.0
10/14	500	+25	0.0
10/13	500	+25	0.0
9/13	500	+25	0.0
9/12	500	+25	0.0
8/12	500	+25	0.0
8/11	500	+25	0.0
8/10	500	+25	0.0
7/10	500	+25	0.0
7/9	500	+25	0.0
6/9	500	+25	0.0

(α = .40 km^{-1} cont'd)

Constellation	Mean Kills	Leakage	Sigma
6/8	500	+25	0.0
5/8	500	+25	0.0
5/7	500	+25	0.0
4/7	500	+25	0.0
4/6	499	+24	2.6
4/5 *	478	+3	21.7

α = .50 km^{-1} Constellation Altitude = 927.64 km

13/15 ** (Initial Constellation Beyond Program Limits)

α = .60 km^{-1} Constellation Altitude = 939.29 km

14/18 ** (Initial Constellation Beyond Program Limits)

α = .70 km^{-1} Constellation Altitude = 1076.00 km

14/20 ** (Initial Constellation Beyond Program Limits)

α = .80 km^{-1} Constellation Altitude = 1140.30 km

18/22 ** (Initial Constellation Beyond Program Limits)

α = .90 km^{-1} Constellation Altitude = 1205.85 km

23/26 ** (Initial Constellation Beyond Program Limits)

α = 1.00 km^{-1} Constellation Altitude = 1265.31 km

27/34 ** (Initial Constellation Beyond Program Limits)

Appendix B

Analysis Design

When working with a model such as HELSTAR, the analyst must determine which parameters should be varied and how these changes would effect the performance of the system. Figure B-1 is a basic schematic of HELSTAR which should help to simplify this discussion.

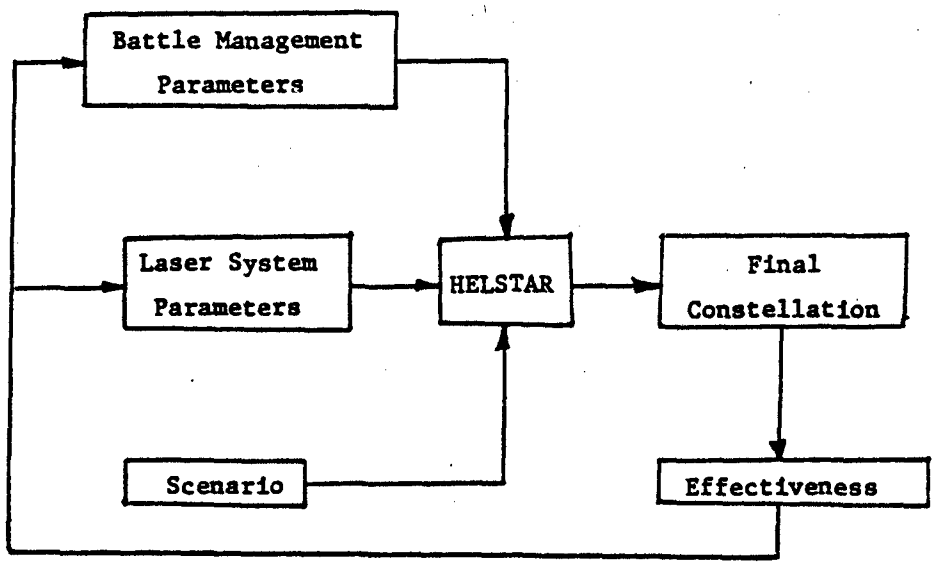

Figure B-1. Schematic of Analysis

For the analysis to have any credible meaning various realistic parameters had to be selected. The battle management parameters had to include:

- success criteria
- ID time or distribution
- retarget time or distribution
- constellation design choice

- minimum engagement altitude

each with several distinct options. The laser system parameters must be chosen from:

- reference intensity at a specified reference range
- sea level absorption/attenuation
- size of target spot
- SBL full duration

with each of these factors also having several distinct options. The scenario studied and analyzed could have many possibilities. Examples are:

- number of missile cells
- number of missiles in each cell
- missile types
- launch times, location of launch
- targets

This can become quite unwieldly as the modeller can use any combination of launch locations, targets and specific missile types to arrive at a unique solution to this problem. Figures B-2, B-3, and B-4 illustrate some of these factors.

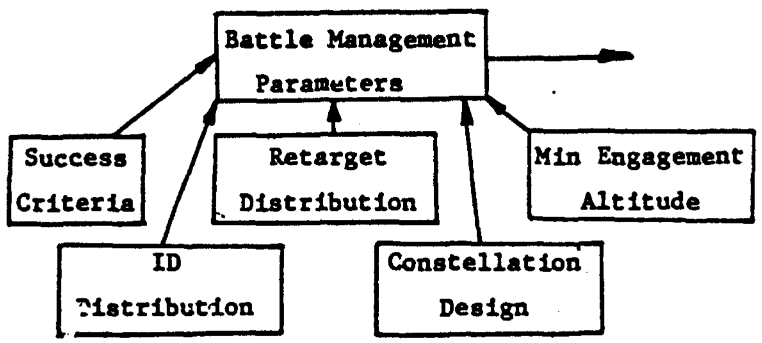

Figure B-2. Battle Management Composition

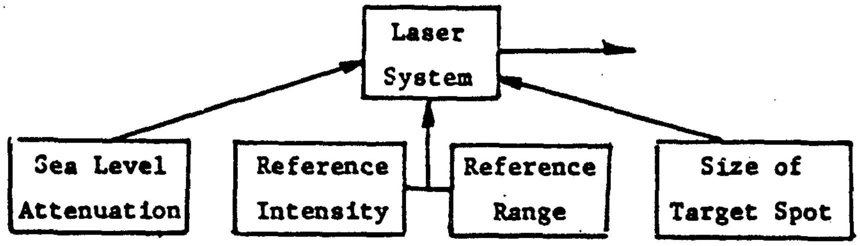

Figure B-3. Laser System Composition

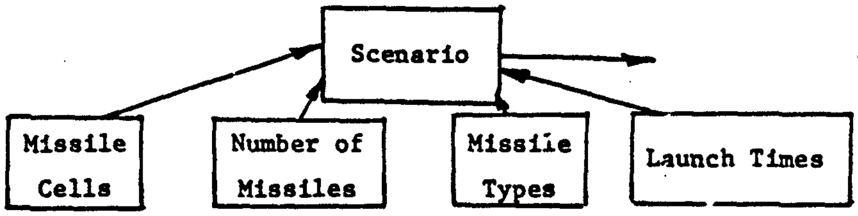

Figure B-4. Scenario Composition

To perform an exhaustive investigation of all variables and their consequent effects on the system would be prohibitive. Therefore, some unique parameters had to be chosen that would give the analyst some insight into system performance with a minimum of computer simulations.

The Battle Management parameters were thought to contain the key factors Minimum Engagement Altitude and Constellation Choice. Indeed there are effects yet to be determined from the other factors but at this stage, a space-based laser defense system is still in the concept definition phase and viable parameters would be difficult to define at this stage. However, minimum engagement altitude and constellation design choice are quite readily defined and easily analyzed, even at this early point.

Likewise the only key parameter of the laser system that could be addressed at this time is sea level attenuation. Actual laser system

parameters, e.g. output power, optics, fuel supply, are poorly defined at this stage but sea-level attenuation is easily computed if wavelength is defined. Since there are five different types of lasers which can be employed for this purpose and each have their own characteristic wavelength, the choice of using sea-level attenuation for this study was easily made.

The matter of scenario choice is a different problem altogether. Many different combinations of launch site, launch time, target location and missile type could be infinitely modeled and analyzed. The selections made for this study were chosen based on logic and computer resource limitations.

Analyses could be made on a number of other parameters not chosen for this study. Perhaps they might have a far greater impact on the effectiveness of the system than those chosen for this study.

Appendix C

Determination of Constellation Altitude

During the investigation of HELSTAR, system performance and efficiency was found to be very dependent on constellation altitude. Even though it is assumed that the reader is familiar and proficient with the program, this appendix will review the altitude determination algorithm used by HELSTAR.

Two critical parameters, the maximum effective slant range to the minimum engagement altitude (RMAXC) and the optimum atmospheric shot angle (BETMIN), are determined by subroutine AMNRMX. To provide the largest coverage angle (PSIMAX) they must be optimized in the constellation design. Figure C-1 depicts the relationship between these three elements.

BETMIN and PSIMAX are initially set to zero and a maximum range for the SBL is determined by AMNRMX after atmospheric transmissivity is calculated by subroutine TRANSY. Atmospheric transmissivity at the minimum engagement altitude must be numerically integrated since it is an exponential function of altitude. By setting the minimum lethal edge intensity, I_{MIN}, equal to the peak intensity on target, I_{TGT}, RMAXC can be determined by

$$RMAXC = R_{TGT} = R_{REF} \left(\frac{I_{REF}}{I_{TGT}} \right)^{1/2}$$

Beam spread on the target (W_{TGT}) can then be calculated by using

$$W_{TGT} = W_{REF} \left(\frac{R_{TGT}}{R_{REF}} \right)$$

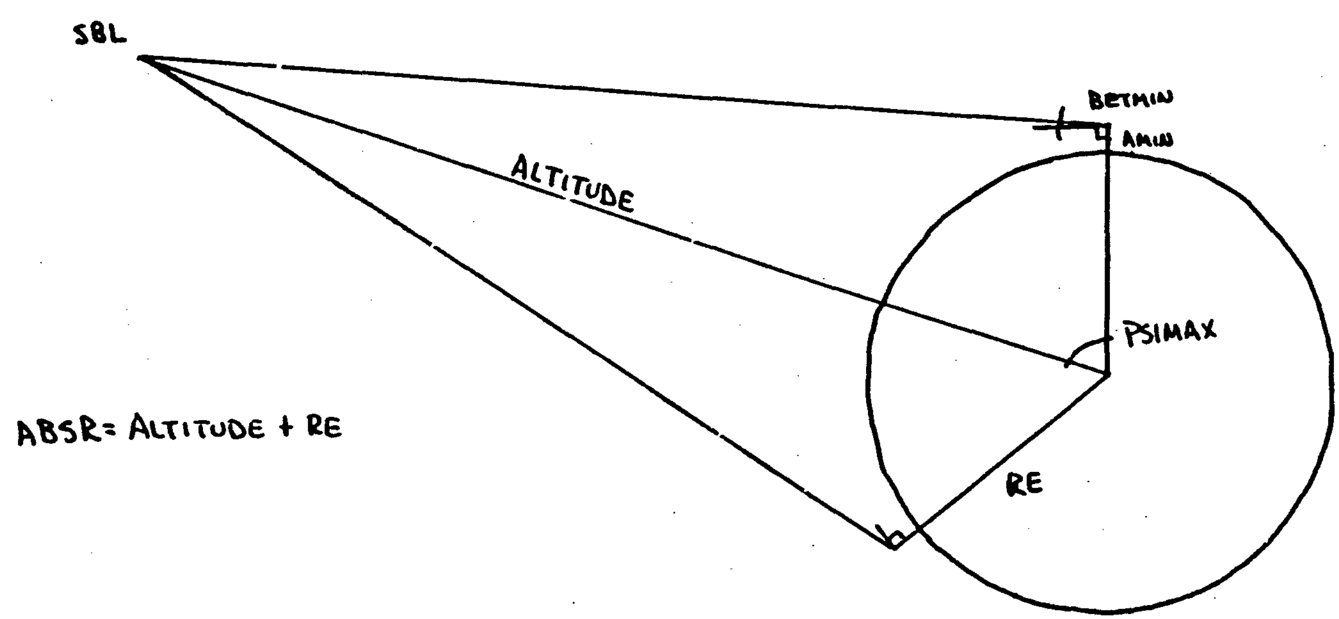

Figure C-1. Relationship Between RMAXC, BETMIN and PSIMAX.

Edge intensity on the target can now be determined by using the value of transmissivity (T) previously calculated by TRANSY

$$I(\text{edge}) = I_{TGT} \exp\left(-.5 \frac{\frac{SPSIZE}{2}^2}{W_{TGT}^{\;2}}\right) T$$

where

$\frac{SPSIZE}{2}$ = radius of minimum lethal spot

If I(edge) is less than the input minimum lethal edge intensity, RMAXC is decremented, new values of I_{TGT}, W_{TGT} and I(egde) are again calculated and the process iterates until I(edge) is greater than or equal to I_{MIN}. At this point, the value of RMAXC is used to determine

$$ABSR = \left[R_{MAXC}^{\;2} + (RE + A_{MIN})^2 + 2R_{MAXC}(RE + A_{MIN}) \sin BETMIN\right]^{1/2}$$

where

RE = radius of the earth

A_{MIN} = minimum engagement altitude

From ABSR the constellation altitude can be determined

$$\text{Altitude} = ABSR - RE$$

The coverage half-angle can be determined by

$$PSI_{CAL} = \cos^{-1}\left[\frac{(RE + A_{MIN} + R_{MAXC} \sin BETMIN)}{ABSR}\right]$$

PSI_{CAL} is then compared with the previous value of PSIMAX, and if larger, the angle BETMIN is incremented .25 degrees. This process continues until the coverage angle peaks and then decreases for larger values of BETMIN. In essence, the value of BETMIN yielding the maximum

value of BETMIN is determined by trial and error. Figure C-2 depicts the logic flow for this process.

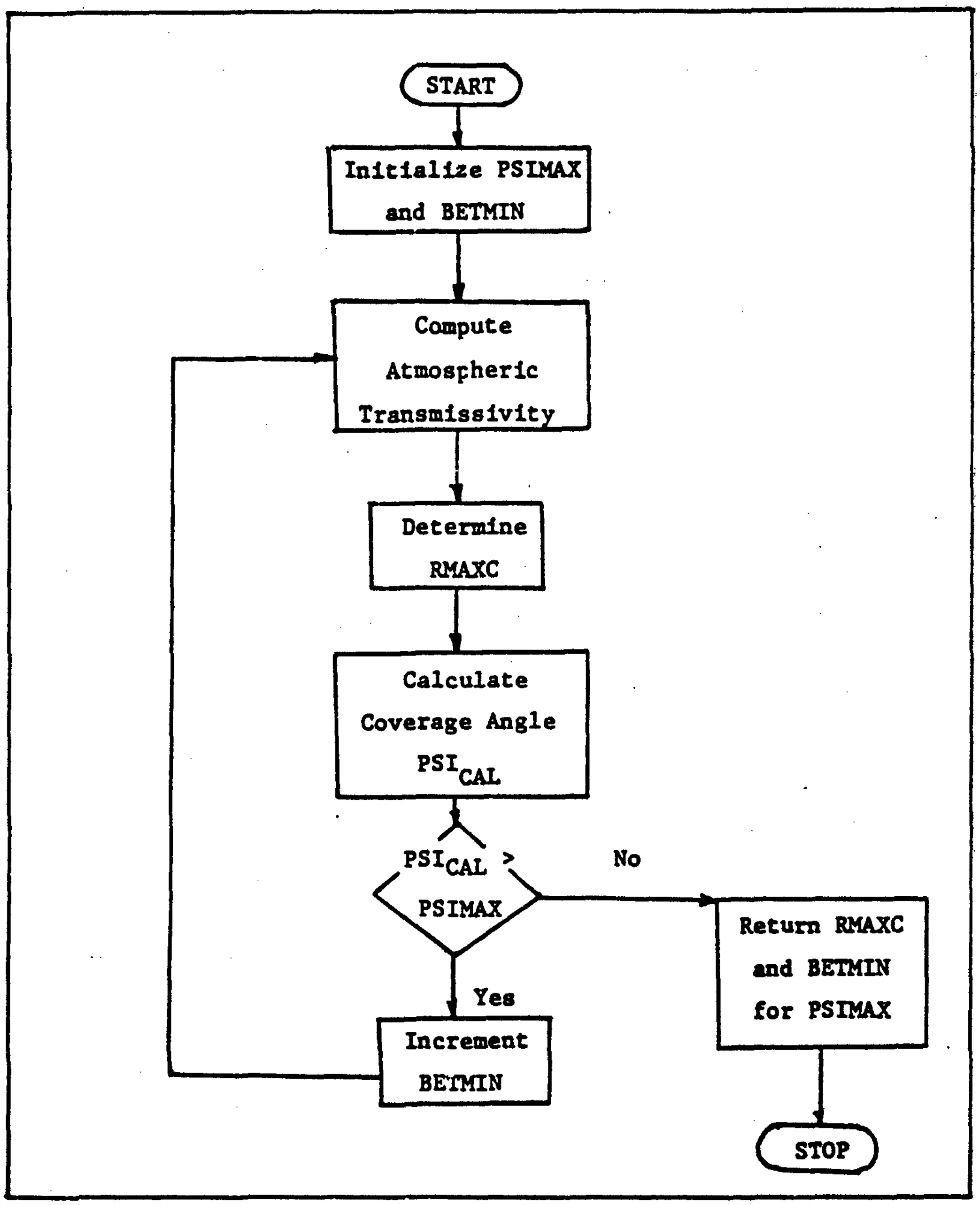

Figure C-2. Logic Flow for Maximum Coverage

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY 2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFIT/GSO/OS/83D-7	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Air Force Institute of Technology 6b. OFFICE SYMBOL (If applicable) EN	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State and ZIP Code) Wright Patterson AFB, Ohio 45433	7b. ADDRESS (City, State and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State and ZIP Code)	10. SOURCE OF FUNDING NOS. PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT NO.
11. TITLE (Include Security Classification) A Parametric Analysis of HELSTAR (Unclass)	

12. PERSONAL AUTHOR(S)
Miklasevich, James (NMN)

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
MS Thesis	FROM 83/06 TO 83/12	83/12/16	106

16. SUPPLEMENTARY NOTATION

Approved for public release: IAW AFR 190-17.
LYNN E. WOLAVER
Dean for Research and Professional Development
Air Force Institute of Technology (AFC)

17. COSATI CODES		
FIELD	GROUP	SUB. GR.

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
HELSTAR, Space-Based Laser, Ballistic Missile Defense, High Energy Lasers, Laser Weapons, Space Defense

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The HELSTAR program is analyzed with a view towards verification and validation. The program is divided into three major areas for parametric study: battle management, laser system and battle scenario. The effects of atmospheric attenuation of laser energy, total number of attacking missiles, type of satellite orbit, and time-dependent launches on total system effectiveness are analyzed.

In the course of the study, the effect of constellation altitude was found to have a significant effect on the size of the final "optimum" constellation. Since this altitude is determined by the program during initialization and cannot be controlled by the user, it can be considered to be a limitation of the program. Also, during the investigation of time-dependent launches, an error was found that led to invalid results. The exact location of this error could not

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☒ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Miklasevich, James	22b. TELEPHONE NUMBER (Include Area Code) (513) 255-5533 22c. OFFICE SYMBOL AFIT/EN

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE.

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be determined.

Aside from the above mentioned limitations, the program was found to generate logical results. It was felt that potential users could use the program with a high degree of confidence that the engagements between ICBM's and space-based lasers were being modelled correctly.